INTERGOVERNMENTAL PANEL ON climate change

Chapter 6

Ocean Energy

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Lenght

Chapter 6 has been allocated a maximum of 34 (with a mean of 27) pages in the SRREN. The actual chapter length (excluding references & cover page) of the original version (prior to TSU commenting and formatting) was 47 pages: a total of 13 pages over the maximum (20 over the mean, respectively).

Expert reviewers are kindly asked to indicate where the Chapter could be shortened in terms of text and/or figures and tables.

References

References of figures/tables are often missing. References from the text that are found missing in the reference list have been highlighted in yellow. In the same manner, references found in the reference list but missing from the text have also been highlighted.

Metrics

All monetary values provided in this document will be adjusted for inflation/deflation and then converted to US$ for the base year 2005.

Figures

Pictures and figures will be replaced by equivalents with higher resolution where necessary.

Headings

The title of subchapter 6.2 was changed back from "Global Technical Resource Potential" to "Resource Potential" as approved by the IPCC Plenary.

Subheadings called "OTEC" have been changed into "Ocean thermal energy conversion". Please make sure to introduce abbreviations again in each subchapter to allow for selective reading. Changes have been done by TSU accordingly.

Chapter 6: Ocean Energy

CONTENTS

EXECUTIVE SUMMARY

Ocean Energy can be defined as energy derived from technologies, which utilize sea water as their motive power or harness the chemical or heat potential of sea water. The technologies for harnessing of ocean energy are probably the least mature of the six principal forms of renewable energy in this Special Report. The energy resources contained in the world's oceans easily exceed present human energy requirements and the energy could be used not only to generate and supply electricity but also for direct potable water production. Whilst some potential ocean energy resources, such as osmotic power from salinity gradients and ocean currents, are globally distributed, other forms of ocean energy are distributed in a complementary way. Ocean thermal energy is principally distributed in the Tropics around the Equator (0° – 35°), whilst wave energy principally occurs between latitudes of 40° - 60°. Further some forms of ocean energy may be able to generate base load electricity, notably ocean thermal energy, ocean currents salinity gradients and, to some extent, wave energy.

Tidal rise and fall energy can be harnessed by the adaptation of river-based hydroelectric dams to estuarine situations. Most other ocean energy technologies are at an early stage of development and none can be truly characterized as commercially competitive with the other lowest cost forms of renewable energy – wind, geothermal and hydroelectric energy. Although basic concepts have been known for decades, if not centuries, ocean energy technology began in the 1970s, only to languish in the post-oil price crisis period of the 1980s. Research and development on a wide range of ocean energy technologies was rejuvenated at the start of the 2000s and some technologies – for wave and tidal current energy – have reached full-scale prototype deployments. Unlike wind turbine generator technologies, there is presently no convergence on a single design for ocean energy converters and, given the range of options for energy extraction, there may never be a single device design.

Worldwide developments of devices are accelerating with, for instance, over 100 prototype wave and tidal current devices under development (US DoE, 2009). Whilst there are no markets presently buying ocean energy converters, the principal investors in ocean energy R&D and deployments are national, federal and state governments, followed by major national energy utilities and investment companies. By contrast, the principal form of device developer is a private small- or medium-scale enterprise (SME). There is encouraging uptake and support from these major investors into the prototype products being developed by the SMEs.

National and regional governments are particularly supportive of ocean energy through a range of initiatives to support developments. These range from R&D and capital grants to device developers, performance incentives (for produced electricity), marine infrastructure development, standards, protocols and regulatory interventions for permitting, space and resource allocation. Presently the north-western [TSU: "NW" replaced by "north-western".] European coastal countries lead development of ocean energy technologies with the North American, north-western [TSU: "NW" replaced by "north-western".] Pacific and Australasian countries also involved.

Environmental impacts of ocean energy converters can be forecast from maritime and offshore oil and gas industries. Increased numbers of widespread deployments will identify key environmental issues. Ocean energy technologies potentially offer fewer environmental risks and thus community acceptance than other renewable energy developments. [TSU: Sentence incomplete? Fewer environmental risks -> higher (?!) community acceptance]. The social impacts are likely to be high, rejuvenating shipping and fishing industries, supplying electricity and/or drinking water to remote communities at small-scale or utility-scale deployments with transmission grid connections to displace aging fossil fuel generation plants. Critically, ocean energy technologies do not generate greenhouse gases in operation, so they can contribute to emissions reduction targets.

Although ocean energy technologies are at an early stage of development, there are encouraging signs that the capital cost of technologies (in $/kW) [TSU: US$ (2005)] and unit cost of electricity generated (in $/kWh) [TSU: US$ (2005)] will decline from their present non-competitive levels to reach the costs of wind, geothermal and hydroelectric technologies. When this occurs, the uptake of ocean energy can be expected to accelerate and ocean energy will form another energy/water supply option for countries seeking to reduce their GHG emissions to meet internationally agreed targets for such reductions.

6.1 Introduction

This chapter discusses the contribution that useful energy derived from the ocean can make to the overall energy supply and hence its contribution to the mitigation of climate change.

The renewable energy resource in the ocean comes from five distinct sources, each with different origins and each requiring different technologies for conversion. These resources are:

- **Wave Energy** – derived from wind energy kinetic energy input over the whole ocean,
- **Tidal Rise and Fall** – derived from gravitational forces of earth-moon-sun system,
- **Tidal and Ocean Currents** – derived from tidal energy or from wind driven / thermo-haline ocean circulation,
- **Ocean Thermal Energy Conversion (OTEC)** – derived from solar energy stored as heat in ocean surface layers and **Submarine Geothermal Energy** – hydrothermal energy at submarine volcanic centres,
- **Salinity Gradients** – derived from salinity differences between fresh and ocean water at river mouths (sometimes called ‘osmotic power’).

Aspects related to resource potential, environmental and social impacts, technology, costs and deployment are considered.

The conversion of resources available in the oceans to useful energy presents a significant engineering challenge. However, the reward may be high with many estimates of the potential energy exceeding world electricity demands (Bhuyan, 2008). Even though the potential resources have been recognised for a long time, technologies for harnessing these potentials are only now becoming feasible and economically attractive, with the exception of tidal barrage systems - effectively estuarine hydro dams - of which a number of plants are operational worldwide (c. 265 MW worldwide).

6.2 Resource Potential

6.2.1 *Wave Energy*

Wave energy is a concentrated form of wind energy. Wind is generated by the differential heating of the atmosphere and, as it passes over the ocean, friction transfers some of the wind energy to the water, forming waves, which store this energy as potential energy (in the mass of water displaced from the mean sea level) and kinetic energy (in the motion of water particles). The size of the resulting waves depends on the amount of transferred energy, which is a function of the wind speed, the length of time the wind blows (order of days) and the size of the area affected by the wind (fetch). Waves grow into open ocean swells by constructive interference, the difference being that waves have periods of less than 10 seconds, whilst swells have greater periods.

The most energetic waves on earth are generated between 30º and 60º latitudes by extra-tropical storms (the so-called “Roaring Forties”). There is also an attractive wave climate within ± 30º of the Equator (where trade-winds prevail most of the year). The wave energy resource is lower here than in temperate areas but has lower seasonal variability. However, doldrums occur in some Equatorial zones.

The total theoretical wave energy resource is very high (32,000 TWh (Mørk et al., 2010), roughly twice the global electrical energy consumption in 2006 (18,000 TWh (EIA, 2008). A map of the global offshore average annual wave power distribution shows that the largest power levels occur off the west coasts of the continents in temperate latitudes, where the most energetic winds and greatest fetch areas occur (Figure 6.1).

The regional distribution of the theoretical annual wave power is presented in Table 6.1. These figures were obtained for areas where theoretical wave power (P) ≥ 5 kW/m and latitude ≤ ±66.5 º. The total annual wave power is 29,500 TWh, which represents a decrease of 8% when we compare with the total figure above.

Table 6.1: Regional Theoretical Wave Power (Mørk et al., 2010)

REGION	**WAVE POWER** (TWh)
West and North Europe	2748
Baltic Sea	34
Mediterranean Sea	324
Southern North Atlantic Archipelagos (Azores, Cape Verde, Canaria Islands)	970
North America Eastcoast	900
North America Westcoast	2325
Greenland	741
Central America	1496
South America Eastcoast	1777
South America Westcoast	2840
North Africa	354
West and Central Africa	673
South Africa	1555
East Africa	907
East Asia	1439
Southeast Asia and Melanesia	2481
West and South Asia	791
Asiatic Russia	1467
Australia and New Zealand	5028
Polynesia	555
TOTAL	29407

*) Areas with lat ≥ 66.56083°N and/or Pannual ≤ 5kW/m were not considered

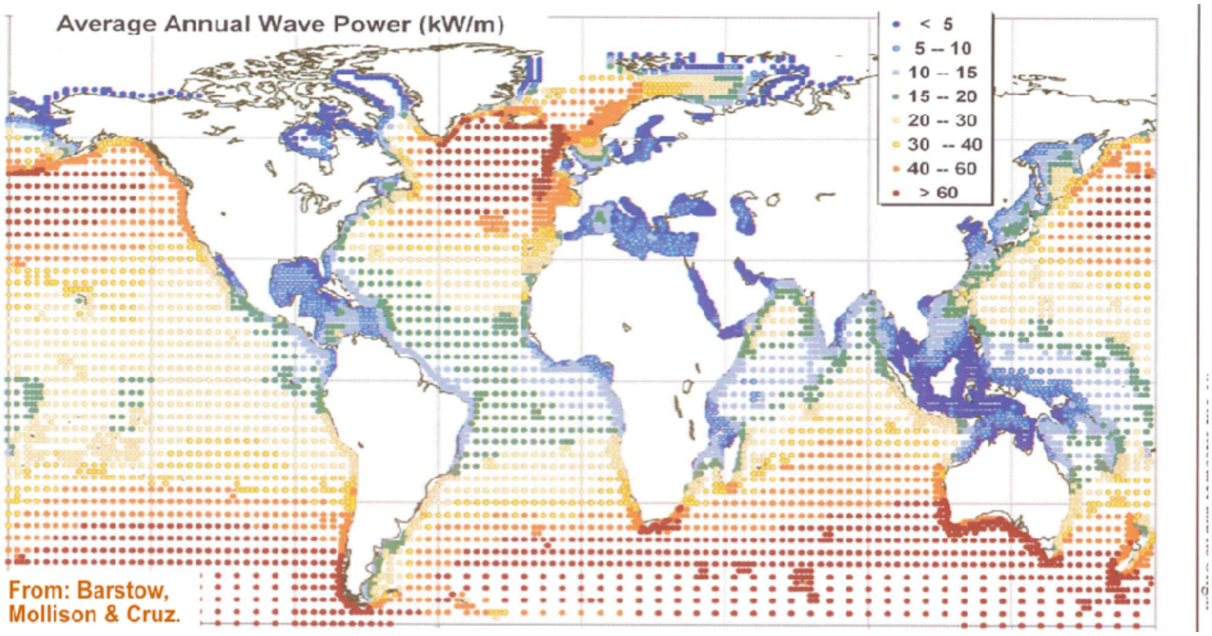


Figure 6.1: Global offshore annual wave power level distribution (Barstow, S., Mollison, D. and Cruz, J., in Cruz, 2008).

Seasonal variations are much larger in the Northern Hemisphere than in the Southern Hemisphere which is an important advantage not recognized yet (Figure 6.2).

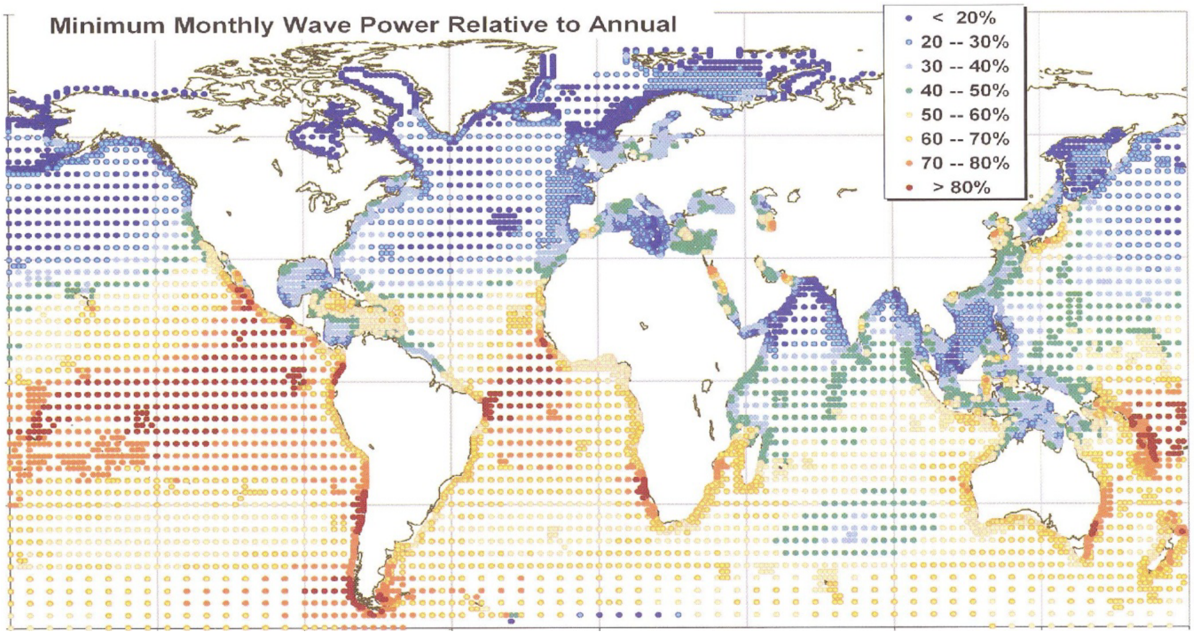


Figure 6.2: Minimum [TSU: monthly] wave power compared to annual [TSU: annual average or annual maximum?] (Barstow, S., Mollison, D. and Cruz, J., in *Cruz*, 2008)

In deep waters, waves travel for very long distances (i.e. tens of thousands of kilometres) with minimal energy dissipation. This has been recognized with swells generated in the Antarctica, Australia and New Zealand that have been observed in California (e.g. Khandekar, 1989). As open sea waves travel towards the shore, when the water depth (*h*) becomes less than half the wavelength, the start to undergo transformations due to frictional interaction with the seafloor

(Lighthill, 1978). The waves start to grow in height and, due to refraction (similar to the optical phenomenon), wave crests tend to become parallel to the bathymetric contours. This, in turn, leads to [TSU: Word "to" was added.] energy concentration in convex zones (e.g. close to capes) and dispersion in concave zones (e.g. in bays). Another cause of resource modification in coastal areas is shelter by neighbouring islands or by the coast itself. As the depth further decreases an early simplified formula states that waves start to break (thus dissipating their energy), when wave height $H < Kh$, with the constant K having values between 0.79 and 0.87 (Sarpkaya and Isaacson, 1981). Another cause of energy dissipation is bottom friction that can be significant when the continental shelf is wide and the sea bottom is rough, as in the west of Scotland, where some frequency components have lost half of their energy between offshore deep water and water depths of 42 m (Mollison, 1985).

Wave information comes mainly from two sources:

1. Data obtained from in-situ measurements, and

2. Remotely-sensed data, e.g. from satellite altimeters

The results of numerical wind-wave modelling have become increasingly accurate. In situ data are obtained by a number of measuring devices, their selection depending on local conditions (namely water depth) and existing structures. Wave measuring buoys are the systems most used for water depth larger than 20 m (see Allender et al., 1989 for a comprehensive evaluation of directional wave instrumentation). For shallower depths seabed-mounted probes (pressure and acoustic) are used. When offshore structures are available (e.g. oil/ gas platforms) measurements by capacity/resistive probes or down-looking infra-red and laser devices are available.

Note that in situ measurements are made at the point where the sensor is located, whereas remotely sensed measurements, using land- or satellite-based radar systems, integrate information from an area.

Satellite-based altimeters make measurements along track, which can be combined to provide global coverage. They have operated since 1991 and presently three satellite-based altimeters are in operation. These are the ENVISAT (European Space Agency), JASON (National Oceanic and Atmospheric Administration) and Geosat Follow-on (GFO; US Navy). Altimeters provide measurements of significant wave height (H_s) with accuracy similar to wave buoys; analytical models to obtain wave period from altimeter data also provide accurate data (Pontes and Bruck, 2008). The main drawback of satellite data is the long Exact Return Period (ERP), which is between 10 and 35 days) and the corresponding large distance between adjacent tracks (0.8º to 2.8 º along the Equator).

Synthetic Aperture Radar (SAR) provides directional spectra that are becoming increasingly accurate, although they are not useful yet for wave energy resource mapping (Pontes et al., 2008). Numerical wind-wave models that compute directional spectra over the oceans, taking as input wind-fields provided by atmospheric models, are by far the largest source of wave information. The WAM model (The WAMDI Group, 1988 and Komen et al., 1994) running at global and regional scales at ECMWF (European Centre for Medium-Range Weather Forecasts, UK) provides high quality wave results. Other institutions run the WaveWatch III (WWIII; Tolman, 2006) model, e.g. NOAA/NCEP, and the UK Meteorological Office model (The Met Office, 2009).

Different types of wave data are complementary and should be used together for best results. For a review of wave data sources, atlases and databases see Pontes and Candelária (2009).

6.2.2 Tide Rise and Fall

Tidal rise and fall is the result of gravitational attraction of the Earth / Moon and the Sun on the ocean. In most parts of the world there are two tides a day (called ‘semi-diurnal’), whilst in other places there is only one tide a day. During the year, the amplitude of the tides varies depending on the respective positions of the Earth, the Moon and the Sun. When the Sun, Moon and Earth are aligned (at full moon and at new moon) maximum tidal level occurs (i.e. spring tides). The opposite tides, called neap tides occur when the gravitational forces of the Moon and the Sun are in quadrature; they occur during quarter moons.

The spatial distribution of the tides varies depending on global position and also on the shape of the ocean bed, shoreline geometry, Coriolis acceleration and atmospheric pressure. Within a tidal system there are points where the tidal range is nearly zero (amphidromic points). However, even at these points tidal currents may flow as the water levels on either side of the amphidromic point are not the same. This is of the result of the Coriolis effect and interference within oceanic basins, seas and bays creating a tidal wave pattern (called an amphidromic system), which rotates around the amphidromic point. See Pugh (1987) for a useful background reference on tidal theory.

Locations with the highest tidal ranges are in Canada (Bay of Fundy), Western Europe (France and United Kingdom), Russia (White Sea, Sea of Okhotsk, Barents Sea), Korea, China (Yellow Sea), India (Arabic Gulf) and Australia. There is a great geographical variability in the tidal range. Some places like the Baie du Mont Saint Michel in France or the Bay of Fundy in Canada experience very high tides (respectively, 13.5m and 17 m), while in other places (e.g. Mediterranean Sea) the tides are hardly noticeable (Shaw, 1997; Usachev, 2008). The global distribution of the M2 constituent of the tidal level, the largest semi-diurnal tidal constituent that is one half of the full tidal range, shows that the major oceans have more than one amphidromic system.

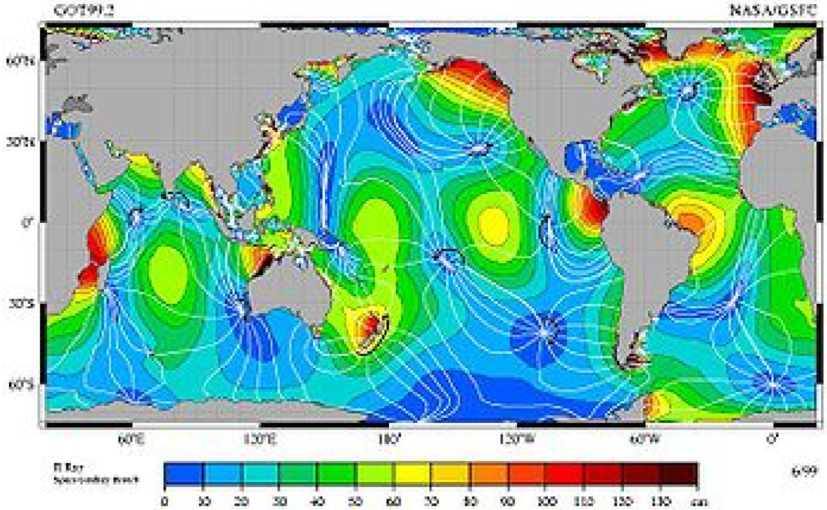


Figure 6.3 - TOPEX/Poseidon: Revealing Hidden Tidal Energy GSFC, NASA. The M2 tidal constituent, the amplitude indicated by color. The white lines are cotidal lines spaced at phase intervals of 30° (a bit over 1 hr).The amphidromic points are the dark blue areas where the lines come together (Ray et al., 2009 [TSU: figure will be replaced with ones with higher resolution. text in figure caption unclear]

Because tidal rise and fall result from astronomical effects, these can be forecasted with a high level of accuracy centuries in advance, although the resultant energy is intermittent. There is therefore little or no hydrological risk associated with devices producing electricity from tidal rise and fall. This is a significant advantage when compared to conventional hydro, to wind or to solar energy.

Conventional tidal rise and fall power stations will generate electricity only at certain times during the tide cycle. The average plant factor observed at power stations in operation varies from 25% to 35% (Charlier, 2003).

It has been estimated that the world theoretical tidal power potential is in the range of 3 TW with 1 TW located in relatively shallow waters (Charlier and Justus, 1993). The effect of climate change on the tidal rise and fall is uncertain but, in the worse case, sea level rise should only result in translation of the mean ocean level, with possible impacts linked to the change in shoreline, and not to changes in tidal range.

6.2.3 Tidal Currents

Tidal currents are the ocean water mass response to tidal rise and fall. Tidal currents are generated by horizontal movements of water, modified by seabed bathymetry, particularly near coasts or other constrictions, e.g. islands. These currents depend on the sinusoidal variation of various tidal components, operating on different cycles, although these flows can be modified by short-term weather fluctuations. Some coasts have single daily tides, whilst others have two tidal cycles per day (i.e. semi-diurnal tides). The potential power of a tidal current is proportional to the cube of the current velocity. For nearshore currents, i.e. in channels between mainland and islands or in estuaries, current velocity varies approximately sinusoidally with time, the period being related to the different tidal components. As a rule of thumb potentially commercially attractive sites require a minimum average sinusoidal current velocity in excess of 1.5 m/s. Below that value (1.0 – 1.5 m/s) evaluation should be on a site-by-site basis. For non-oscillating currents, the maximum current velocity should exceed 1.0 m/s, whereas in the range 0.5 to 1.0m/s its practical exploitation depends on site evaluation.

In the United States a methodology for the assessment of tidal current energy resource has been proposed (Hagerman et al., 2004). An atlas of the wave energy and tidal resource has been developed for the UK, which includes tidal current energy (UK Department of Trade and Industry, 2004). Similar atlases have been published for the European Union (CEC, 1996; Carbon Trust Marine Energy Challenge, 2004) and for far-eastern countries (CEC, 1998).

In Europe the tidal energy resource is of special interest for the UK, Ireland, Greece, France and Italy. A total of 106 promising locations were identified and it was estimated that, using present-day technology, these sites could supply 48 TWh/yr to the European electrical grid network. In China it has been estimated that 7,000 MW of tidal current energy are available. Locations with high potential have also been identified in the Philippines, Korea, Japan, Australia, Northern Africa and South America.

The predictability of marine currents and the potential [TSU: potentially] high load factor (20-60%) are important positive factors for their utilization. Sites with pure tidal flow in most cases offer capacity factors in the 40-50% range. For non-tidal flows this range increases to the order of 80%.

6.2.4 Ocean Currents

In addition to oceanic currents associated with tidal flows in coastal regions, there is also significant current flow potential in the open ocean. The large-scale circulation of the oceans is concentrated in various regions – notably the western boundary currents associated with wind-driven circulations – some of which offer sufficient current velocities (~2 ms^{-1}) to drive present-day current technologies (Leaman et al., 1987). These include the Agulhas/Mozambique Currents off South Africa, the Kuroshio off East Asia, the East Australian Current, and the Gulf Stream off eastern

North America (Figure 6.4). Other current systems may also prove feasible with improvements in turbine efficiencies. The most well-characterized of these systems is the Gulf Stream, and it is discussed here as a promising case study.

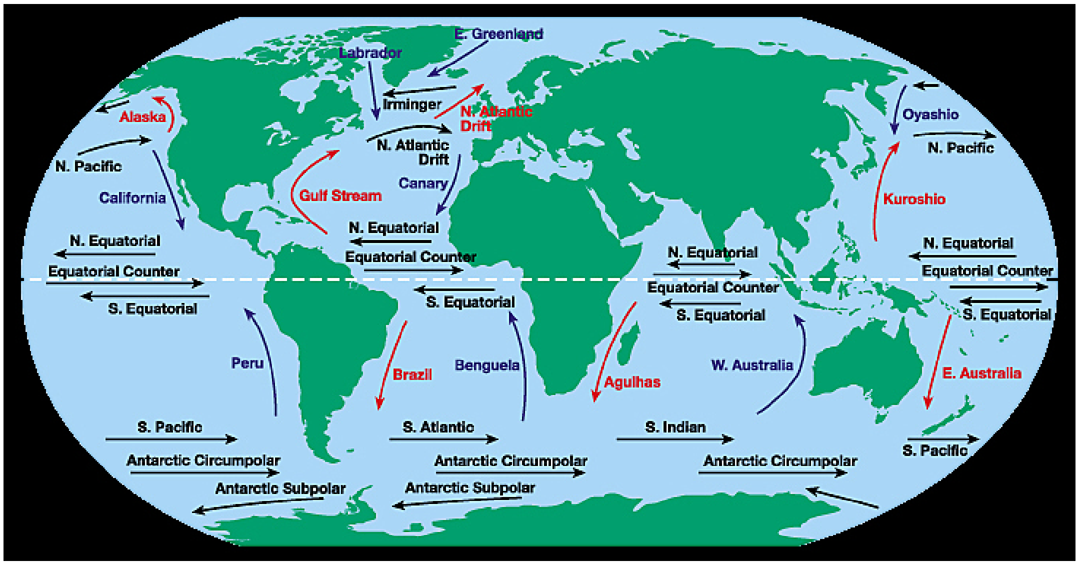


Figure 6.4: Surface ocean currents, showing warm (red) and cold (blue) systems (Windows to the Universe, 2009).

The potential of the Florida Current of the Gulf Stream system for power generation was recognized decades ago at the "MacArthur Workshop" (Stewart, 1974). Although the workshop concluded that the opportunity to generate electrical power from the Florida Current's ~25 GW potential was worth exploring, its recommendations have languished, during which time various oceanographic measurement programs provided additional useful background on the possibilities (e.g. Raye, 2001).

Cross-sections of the current show a core current region 15 - 30 km off the Florida coast and near the surface (Figure 6.5). This core region, although variable, represents the greatest potential for power generation. As the return flow of the Atlantic Ocean's subtropical gyre, the Florida Current flows strongly year around, exhibiting variability on various time and space scales (e.g. Niiler and Richardson, 1973; Johns et al., 1999).

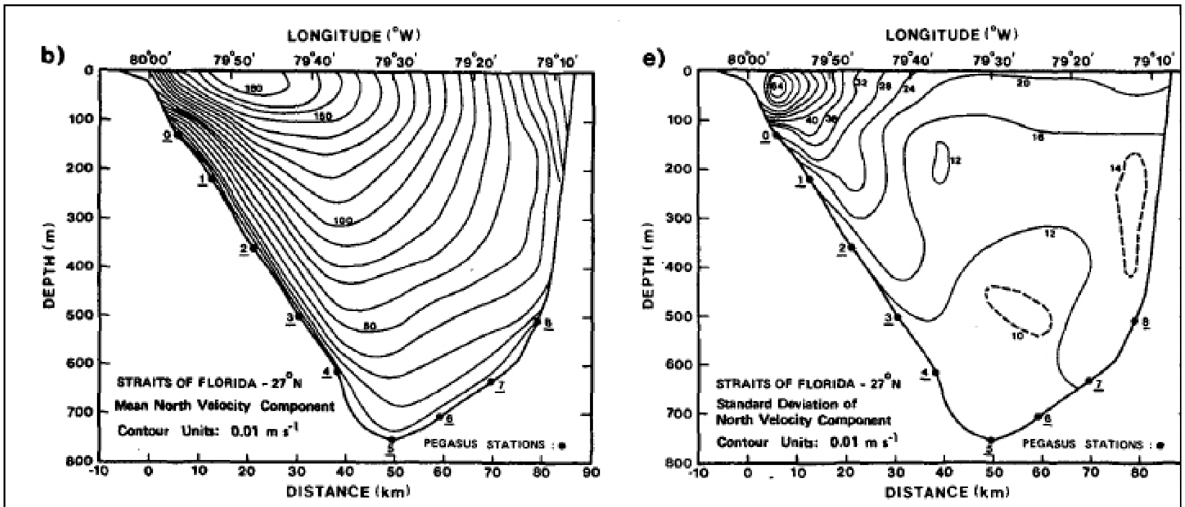


Figure 6.5: Averaged W-E cross-section of northward current in the Florida Straits at 27°N, 1982-1984 (left) and its standard deviation (right). Peak averaged velocity is >1.8 m s^{-1}. Near-shore eddies are the large, near-surface signal in the standard deviation. The flow inside the 180 cm s^{-1} contour represents about 3.5 GW (Leaman et al., 1987).

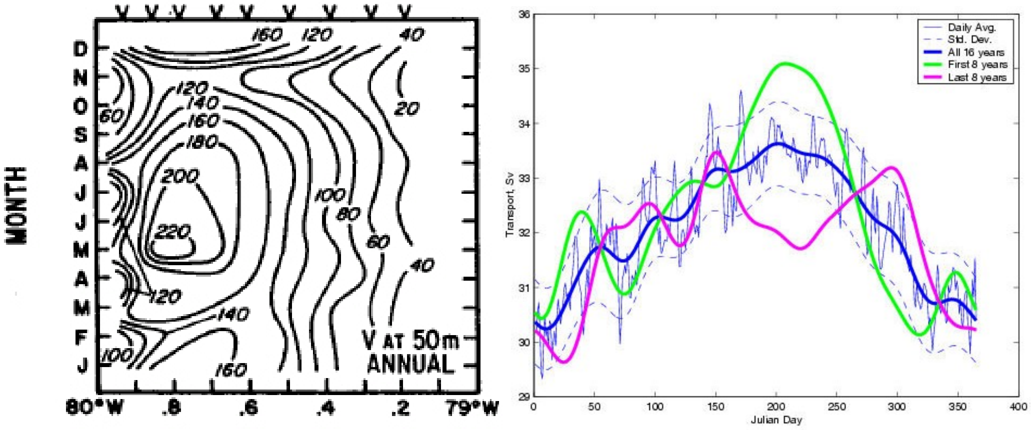


Figure 6.6: Left: Contours of 50-m northward current at 27°N in the Florida Straits, 1982-1984, in cm s^{-1} (Leaman et al., 1987). Right: Channel-integrated transport, 10^6 m^3 s^{-1} (=Sv), showing daily and interannual variability of annual cycle (Baringer and Larsen, 2001). 16 years of data as reproduced at NOAA website.

Figure 6.6 shows (left) the 50-m variability on the annual time scale (for the two years of the Leaman et al. data), and (right) longer-term variations of the system's overall transport. Note that the summertime peak flows are in phase with electrical load demand in South Florida population centers. [TSU: captions of figure 6.6 is doubled]

6.2.5 Ocean Thermal Energy Conversion

The most direct harnessing of ocean solar power is probably through an ocean thermal energy conversion (OTEC) plant. Among ocean energy sources, OTEC is one of the continuously available renewable resources which can contribute to base load power supply, substituting this way large quantities of fossil fuel now employed to generate power.

OTEC potential is considered to be much larger than the other ocean energy types (UNDP, UNDESA, WEC, 2000), and also it has ample distribution of the resource throughout the whole world between the two tropics, although experimental and pilot devices are rare and there is no current commercial exploitation.

From the total solar input received by the oceans, only 15% is retained as thermal energy. Since the intensity falls exponentially with depth, the absorption is concentrated at the top layers. Typically in the tropics, surface temperature values are in excess of 25 °C, whilst 1 km below, the temperature is between 5-10°C.

As the warmer (and hence lighter) waters are at the surface, there are no thermal convection currents going up and down, and due to the very low temperature gradients, heat transfer by conduction is negligible. So with neither of the major mechanisms of heat transfer operating, a stable system results: the surface layers remain warm and deeper layers remain cold; thus the system of both layers is like a practically infinite heat source (top layers) and a practically infinite heat sink (deep layers) with a separation of about 1,000 m between them, that occurs naturally and allows the use of heat engines. This temperature difference varies with latitude and season, with the maximum at tropical, subtropical and equatorial waters. Hence in general, the Tropics are the best locations for OTEC systems, as Claude demonstrated with his experiment in Matanzas Bay, Cuba, in 1930.

There is general agreement that the sea water minimum temperature difference of 20° C should be available to operate an OTEC power cycle. Both coasts of Africa, the tropical west and southeastern coasts of the Americas and many Caribbean and Pacific islands are situated where sea water decreases from a surface temperature of 25-30° C to 4-7° C at depths varying from 750 to 1,000 m. An optimistic estimate of the global resource is 30,000 to 90,000 TWh (Charlier and Justus, 1993).

An OTEC resource map showing annual average temperature differences between surface waters and the water at 1,000 meters depth shows a wide tropical area of potential 20+° C temperature difference is generally considered adequate for OTEC (Figure 6.7). Almost everywhere in the Equatorial zone there is [TSU: The verb "has" has been replaced by "there is".] potential for installing OTEC facilities. Countries, which have the OTEC resource within one mile from their shores, could potentially construct the onshore facilities at considerably reduced costs (UN, 1984). A number of Pacific and Caribbean islands could thus potentially take advantage of OTEC (UN, 1984).

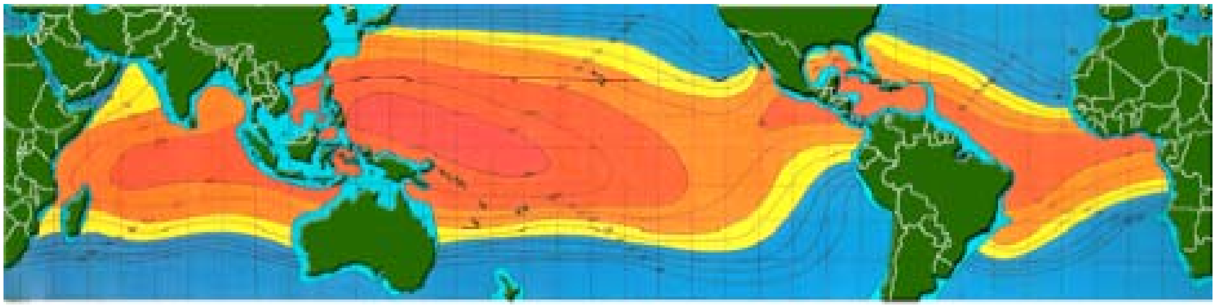


Figure 6.7: OTEC Resource Map (Lockheed-Martin, 2009). [TSU: legend is missing]

Ocean thermal energy conversion is essentially a heat exchange process. However, significant amounts of heat are injected into the ocean from submarine volcanic activity as oceanic spreading ridges. Hydrothermal vents, called 'black smokers', produce plumes of superheated water (c. 350° C) with entrained sulphide minerals, containing gold, silver, copper, lead, zinc and rare earth elements. Most oceanic spreading ridges usually occur at considerable depths (c. 2,000 m) but some, such as in the Gulf of California and the Tonga-Kermadec Arc, north of New Zealand, have submarine geothermal systems at much shallower depths. These shallower resources may be accessible as a form of ‘extreme’ ocean energy thermal energy conversion (Alcocer and Hiriart, 2008).

6.2.6 Salinity Gradient

Since freshwater from rivers debouching into saline seawater is globally distributed, osmotic power could be generated and used in all regions - wherever there is a surplus of fresh water. Feasibility studies must be conducted before any osmotic power plant is constructed to ensure that each river discharging into the ocean can provide sufficient freshwater. Estuarine/deltaic environments are most appropriate, because of the potential for large volumes of both freshwater and seawater.

The first water quantity assessments for osmotic power potential were based on a methodology, which used average discharge and low flow discharge values. Low flow is defined as the 80th percentile of the flow regime, i.e. the low flow is exceeded 80% of the time. Freshwater extraction for electricity generation would not be possible in low flow conditions.

A number of other factors must also be considered in defining the local potential for an osmotic power plant. These are:

- River water volume regime, especially low flow periods
- Salinity differences between the freshwater and sea water
- Freshwater and sea water quality, due to the risk of fouling of the membranes
- Characteristics of the membrane and the membrane element used, particularly its ability to withstand fouling by polluting substances
- Physical and chemical conditions at the site (usually a river delta or estuary).

These factors will be essential to determine whether the development of a commercial Pressure Retarded Osmosis (PRO) power plant is economically viable (see Section 6.3.6).

Other environmental factors may also be taken into consideration:

- Lateral river migration may be a challenge in some areas, as river channels are not always stable systems
- Erosion and deposition of particulate material may cause the channel to change its form and pathway over time. Typical areas where this occurs are areas subject to significant land use changes, areas with heavy erosion processes, or areas where the downstream parts of rivers run through low-lying land without erosion protection works.

Any installations in estuarine/delta areas should therefore be preceded by environmental assessments, in order to determine the risk for channel migration.

The global generation capacity potential for osmotic power generation has been calculated as 2.6 TW (Wick and Schmitt, 1977). More recently, the annual generation potential has been calculated as 1,650 TWh (Scråmestø, Skilhagen and Nielsen, 2009). In Europe alone there is a potential to generate 180 TWh.

Since osmotic power will effectively generate baseload electricity, this form of generation could make a considerable contribution to security of supply, portfolio diversity and grid strengthening.

6.3 Technology and Applications

6.3.1 Introduction

This section describes the state of the technologies used to extract energy from the five [TSU: Ocean and tidal currents are treated separately in section 6.2. but counted as one here] primary ocean energy [TSU: "energy" added.] resources described in section 6.2. Ocean energy may be the least advanced both in terms of technology developments and deployment of all the renewable energy sources covered by this report. The technologies described in this section range mostly from the conceptual stage to the prototype stage, but few technologies have matured to commercial availability. Presently there are many technology options for each ocean energy source but, with the exception of tidal rise and fall barrages (which utilize the experience of the hydro-electric industry), there has been relatively [TSU: The adjective is missing?] convergence, due to a fundamental lack of operating experience. In spite of their nascent development, ocean energy technologies show great promise beyond the near-term, in light of the abundant globally distributed resources. Over the past four decades, other marine industries (primarily petroleum industry) have enabled significant advances in the fields of offshore materials, offshore construction, corrosion, undersea cables, data and communications. Ocean energy can directly benefit from these advances. Consequently, the success of ocean energy technologies does not depend on any new or major technological breakthrough. Most technology development is focused on the application of basic hydrodynamic principles to engineer new energy extraction and conversion systems. In addition, much of the technological uncertainty can be reduced to more routine questions of cost and reliability.

6.3.2 Wave Energy

There is a wide variety of wave energy technologies representing a range of operating principles that have been conceived, and in many cases demonstrated, to convert energy from waves into a usable form of energy. Major variables include the method of wave interaction (heaving, surging, pitching, and hydrostatic pressure), as well as water depth and distance from shore (shoreline, near-shore, offshore). Wave energy can be resolved into two forms – potential energy, caused by gravity, and kinetic energy, caused by the water motion. The energy can be resolved into three components:

- Heave – the vertical component caused by gravity
- Surge – the horizontal component
- Pitch – the rotation component of any wave

Devices have been designed to capture one or more of these components, so there are generic designs that seek to extract energy from heave, from surge and from combinations of all three components.

Recent reviews have identified over 50 wave energy devices at various stages of development (Falcão, 2009; Khan and Bhuyan, 2009 and DoE, 2009 (Figure 6.8)).

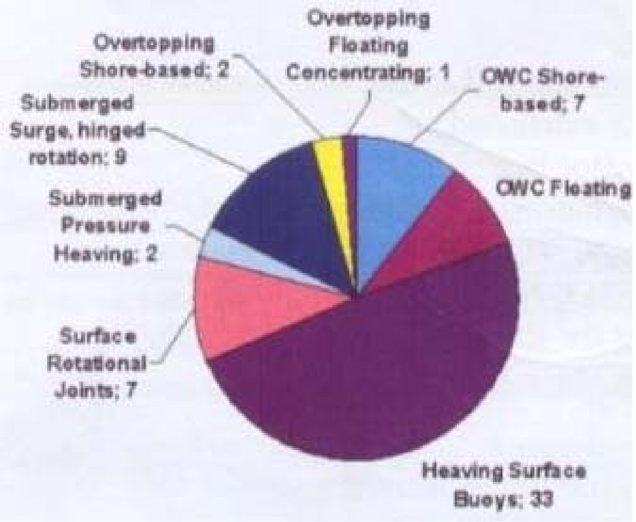


Figure 6.8: Breakdown of wave device types [TSU: Please insert source. Consistency with figure 6.9?]

The dimensional scale constraints of wave devices have not been fully investigated in practice, but the dimension of wave extraction devices in the direction of wave propagation is generally limited to lengths below the scale of the dominant wavelengths that characterize the wave power density spectrum at a particular site. As a result large-scale electricity generation from wave energy will require large arrays of modular devices, rather than increasing scale devices.

Several methods have been proposed to classify wave energy systems (e.g. Falcão, 2009, Khan and Bhuyan, 2009 and DoE, 2009). The classification systems like the Falcão system (Figure 6.9) are sorted mainly by the principle of operation. The first column is the genus, the second column is the location and the third column represents the mode of operation.

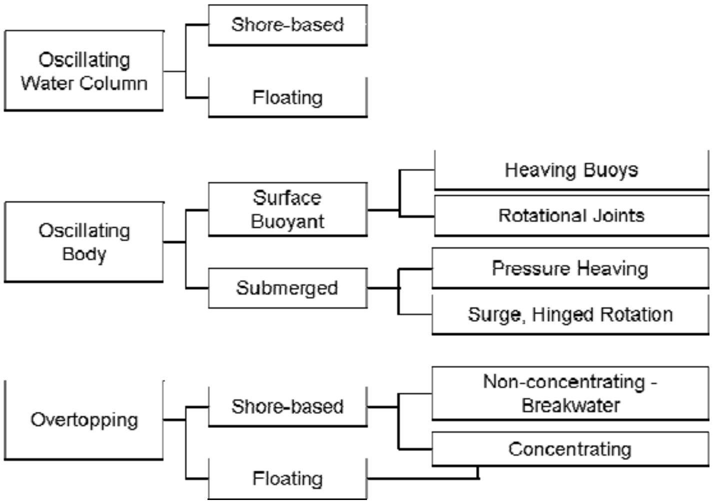


Figure 6.9: Wave energy technologies – Classification based on principles of operation (Falcão, 2009).

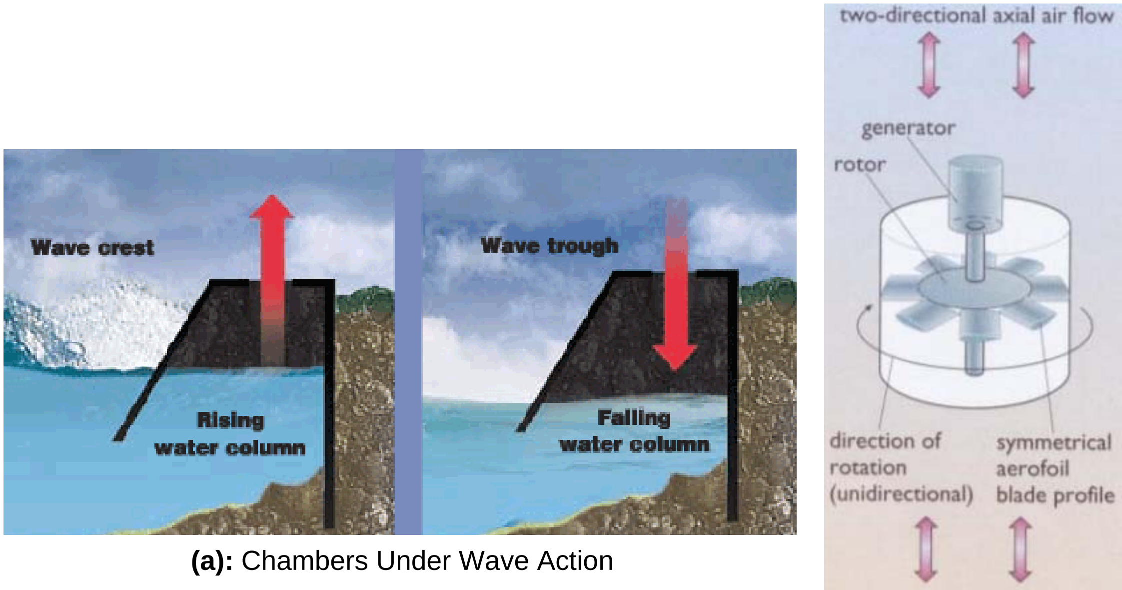
Oscillating water columns [TSU: Please consider using level 4 heading] – Oscillating water column (OWC) are wave energy converters that use wave motion to trap a volume of air and compress it in a closed chamber, where it is exhausted at high velocity through a specialized ducted air turbine coupled to an electrical generator that efficiently converts the kinetic energy of the moving air into electric energy. When the wave recedes, the airflow reverses and fills the chamber, generating another pulse of energy (Figure 6.10a). The turbine is a self-rectifying turbine, generally a Wells turbine (Figure 6.10b). An OWC device can be a fixed structure located at the shore, bottom-mounted in the nearshore or a floating system moored in deeper waters. Shore-based OWC devices can be cliff-mounted or part of a man-made breakwater. Generically, such devices are referred to as ‘terminator’ devices, as they terminate the wave.

Oscillating-body systems [TSU: Please consider using level 4 heading] – Oscillating-body (OB) wave energy conversion devices use the incident wave motion to induce differential oscillating motion between two bodies of different mass, which motion is then converted into a more usable form of energy. OBs can be surface devices or, more rarely, fully submerged. Commonly, axi-symmetric surface flotation devices (buoys) use buoyant forces to induce heaving motion relative to a secondary body that can be restrained by a fixed mooring (Figure 6.11). Generically, these devices are referred to as ‘point absorbers’, because they are non-directional. Another variation of floating surface device uses angularly articulating (pitching) buoyant cylinders linked together. The waves induce alternating rotational motions of the joints that are resisted by the power take-off device. Generically, these devices are called ‘attenuators’, because they attenuate the incident wave energy without terminating it.

Some OB devices are fully submerged and rely on oscillating hydrostatic pressure to extract the wave energy. An oscillating buoyant part is forced down by increasing hydrostatic pressure under a wave crest and up as the pressure decreases under the wave trough with captured interior air acting as a pressure spring. Pitch and surge forces can also be used to induce motion in another form of oscillating device.

Overtopping devices [TSU: Please consider using level 4 heading] - An overtopping device is a type of wave terminator that converts wave energy into potential energy by collecting surging waves into a water reservoir at a level above the free water surface. The reservoir drains down through a conventional low-head hydraulic turbine, Figure 6.12. These systems can be offshore floating devices or incorporated in shorelines or man-made breakwaters.

Power Take-off devices [TSU: Please consider using level 4 heading] - In most cases, the converted kinetic energy or potential wave energy is in turn converted to either electricity or to a pressurized working fluid via a secondary power take-off device. Real time wave oscillations will produce corresponding electrical power oscillations that may degrade the energy quality to the grid. In practice, some method of short-term energy storage (durations of seconds) may be needed to smooth the energy delivery. Optimal wave energy absorption involves some kind of resonance, which implies that the geometry, mass, or size of the structure may be linked to wave frequency.



(a): Chambers Under Wave Action

(b): Wells Turbine

Figure 6.10: Oscillating Water Column

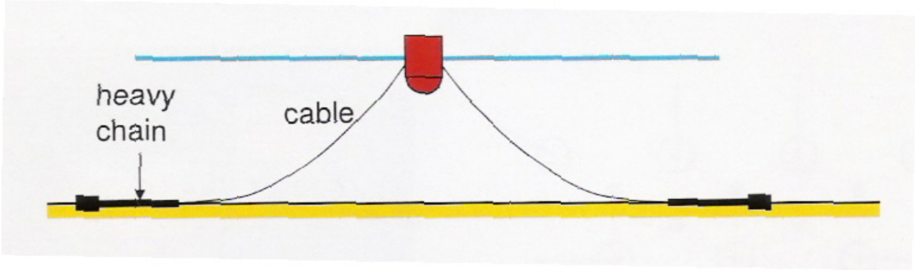


Figure 6.11: Oscillating-Body System

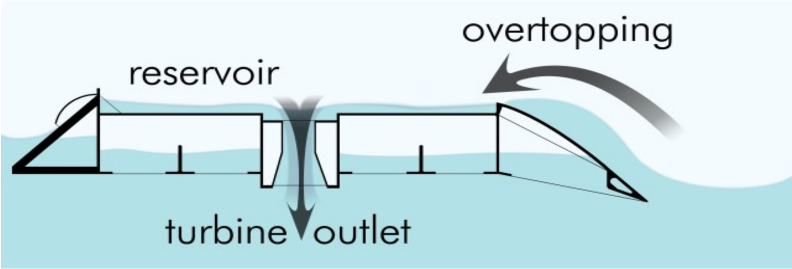


Figure 6.12: Overtopping Wave Terminator

[TSU: Please add sources for figures 6.10, 6.11 and 6.12.]

6.3.3 Tide Rise and Fall

Historically the development of tidal rise and fall hydropower has been based on estuarine developments, where a barrage encloses an estuary, which creates a single reservoir (basin) behind it and incorporates generating units. More recently, barrage configuration has moved to dual-basin mode. One of the two basins fills at high tide, whilst the other is emptied at low tide. Turbines are located between the basins. Two-basin schemes offer advantages over normal schemes in that generation availability can be adjusted with high flexibility, such that it is possible to generate almost continuously. In typical estuarine situations, however, two-basin schemes are very expensive to construct due to the cost of the extra length of barrage. There are some favorable geographies, however, which are well suited to this type of scheme, such as very shallowly shelving coastlines, like the Severn Estuary in southwest [TSU: "SW" has been replaced by "southwest"] England.

The most recent advances focus now on offshore basins (single or multiple), located away from estuaries, which offer greater flexibility, in terms of capacity and output, with little or no impact on delicate estuarine environments. These are called 'tidal lagoons' and rely on the construction of a multi-basin structure. Water is passed between the three basins to allow for continuous electricity generation (Figure 6.13).

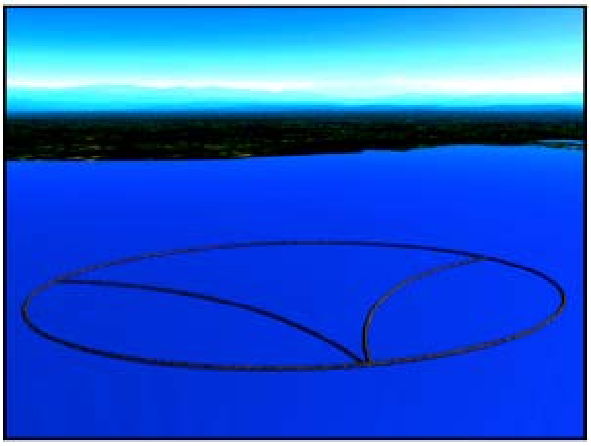


Figure 6.13: TidalElectric's proposed 3-pool Tidal Lagoon (www.tidalelectric.com) [TSU: status of source?]

The conversion mechanism most widely used to produce electricity from tidal rise and fall is the 'bulb-type' unit. A bulb-type unit is a hydroelectric power unit installed in a duct with its centreline coinciding with the flow axis (Figure 6.14). Usually, these units only generate in one direction - either the ebb or flow (simple effect) - and are passive when the tidal flow reverses. In some locations, such as La Rance, the units can generate in both directions (double effect) and may also offer the possibility of pumping, when the tide is high in order to increase the storage in the basin under a low head and with a high efficiency.

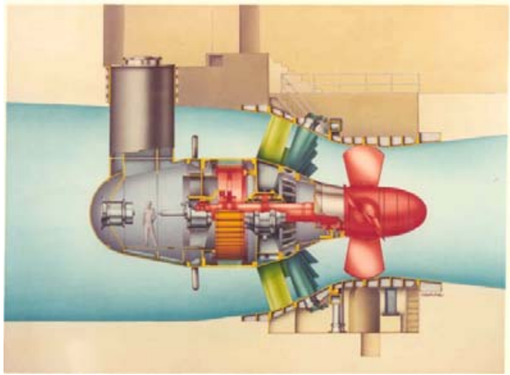


Figure 6.14: Cross section of a bulb unit bay at La Rance, France (courtesy EDF) [TSU: status of source?]

Bulb technology may be improved, for instance with gears allowing different rotation speeds for the turbine and the generator or with variable frequency generation allowing better outputs for the various operating ways and heads. For important schemes and average tidal range between 4 and 8 m, the usual unit capacity will probably be between 20 and 50 MW.

Other types of units have been installed at the 20 MW Annapolis tidal power station in Canada (Figure 6.15)) and in the 1.5 MW Kislaya Guba prototype tidal power station in Russia (orthogonal units). Those new types seem to offer an attractive solution in terms of simplicity, equal efficiency in both directions and cost reduction but have not yet proven their industrial viability.

Figure 6.15: 20 MW tidal power plant at Annapolis Royal, Nova Scotia, Canada. [TSU: Please add source]

Control gates are usually installed in order to facilitate filling or emptying of the basin in order to improve power generation performance and turbines may be used for pumping (as well as generation) to improve storage. The problem of corrosion due to salt water has been solved at the La Rance power station by relying on induced current cathodic protection and by using special materials, surface treatment or electrochemical system. These methods have been applied to units, pipes and gates.

Power plants may be built in situ within cofferdams or pre-fabricated in caissons (steel or reinforced concrete) and floated to site. The caisson solution is particularly adapted to remote sites: caissons with several turbines totalling 200 MW may be used (e.g. at the Sihwa Barrage in the Republic of Korea).

As for embankment dams, the choice of solutions is linked with availability of nearby materials. The underwater parts of barrages may be constructed from sandy materials, often available by dredging in tidal areas. The upper part may use rock fill or pre-fabricated reinforced concrete caissons. Waterproofing may use grouting or diaphragm walls. The necessary waterproofing is not always as perfect as for high onshore dams, because the water head is relatively low and some leakage economically acceptable.

6.3.4 Tidal and Ocean Currents

Technology to extract kinetic energy from tidal, river, and ocean currents are under development, but tidal energy converters are the most common to date. The main difference between tidal and river/ocean current turbines is that river and ocean currents flow in a single direction while tidal turbines reverse flow direction two or four times per day during ebb and flood cycles. Flow reversals provide convenient slack-water periods when installation, service, and inspections can take place.

Several methods have been proposed to classify tidal and ocean current energy systems (Khan et al., 2008; US DOE, 2009 (Figure 6.16)). Usually, they are classified based on the principle-of-operation. Examples of axial flow turbines, (Van Zwieten et al., 2006a; Verdant, 2009), cross flow turbines (Li and Calisal, 2010; Ponte Di Archimede, 2009) and reciprocating devices (Bernitsas et al., 2006) are also shown in Figure 6.17.

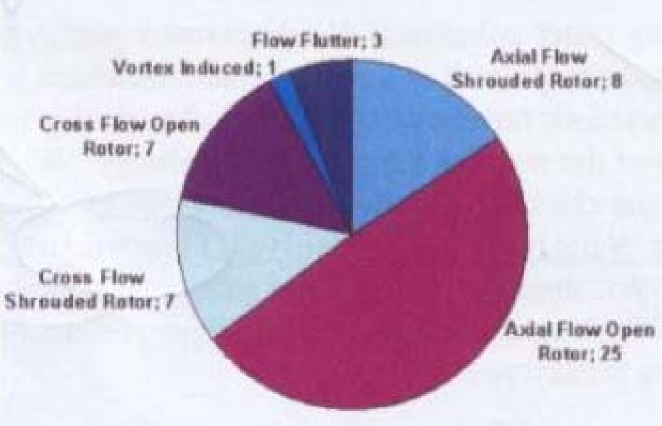
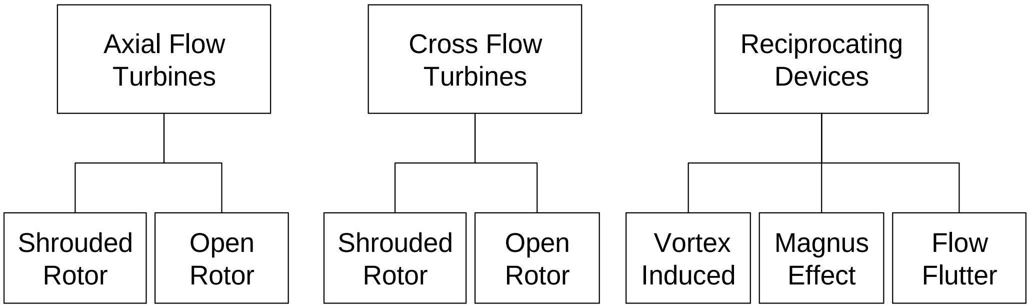


Figure 6.16: Breakdown of tidal and ocean current device types. [TSU: Please insert source. Consistency of naming with figure 6.17?]



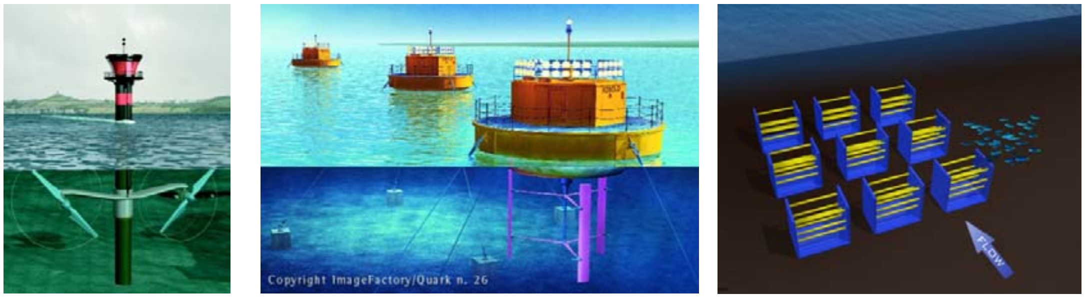


Figure 6.17: Current tidal and ocean energy technologies, classification chart is based on principles of operation with examples of illustrations showing, from left to right, axial flow turbines (courtesy of Mr. Fraenkel) [TSU: status of source?], cross flow turbines (courtesy of Professor Coiro) [TSU: status of source?]and vortex shedding induced vibration reciprocating device (courtesy of Professor Bernitsas) [TSU: status of source?].

Many of the water current energy conversion systems resemble wind turbine technology, but marine turbines must also account for reversing flow, cavitation, and harsh underwater marine conditions (e.g. salt water corrosion, debris, fouling, etc). Axial flow turbines have been widely proven in wind turbines with extraction efficiencies of 45% to 50% based on the total kinetic energy. Although there are offsetting benefits, cross flow rotors are slightly less efficient than axial flow machines with target efficiencies of about 40%. Axial flow turbines in tidal flows must respond to reversing flow directions while cross flow turbines can accept flow direction changes without a mechanical response. Generally, axial flow turbines are designed to change the yaw position of the nacelle 180 degrees in response to tidal flow reversals, or alternatively, the rotors are designed to accept flow from two directions with a fixed yaw position, but with some performance penalty.

Several axial flow and cross flow designs incorporate shrouds (also known as cowlings or ducts) around the outer diameter of the rotor (e.g. Lunar Energy, 2009; Clean Current 2009; Bluenergy 2009). Shrouds can help improve hydrodynamic performance by increasing the velocity of the flow through the rotor and reducing tip losses, but the cost of the shroud may be offset by the additional energy capture. Also, since shrouds encircle the outer path of the blade tip, they could provide some protection against impacts with marine life, although no evidence yet exists to suggest that this is a significant problem or that a shroud would reduce impact frequency. The cost effectiveness and ancillary benefits of shrouded water current turbines have not yet been fully evaluated and further testing and analysis is still needed. The scale of water current devices in rivers and tidal currents will be driven by the external dimensions of the channel transects, in which they are installed and by navigational constraints that require minimum water clearance for vessels.

Capturing the energy of open-ocean current systems requires essentially the same basic technology as doing so in tidal flows, but some of the infrastructure involved will differ. In particular, for deep-water applications, fixed bottom support structures will be replaced with mooring lines and anchor systems, and neutrally buoyant turbine/generator modules will be required or the systems will be attached to other structures, such as an offshore platform (Van Zwieten et al., 2006a; Ponte Di Archimede, 2009). Whether the turbines are bottom fixed or floating, it is likely that these modules will also have hydrodynamic lifting designs to allow optimal and flexible vertical positioning (Van Zwieten et al., 2006b; Venezia and Holt, 1995; Raye, 2001). In addition, open ocean currents will not pose a restriction to the rotor size due to lack of channel constraints. Therefore, ocean current systems may have larger rotors.

Reciprocating devices are generally based on basic fluid flow phenomena such as vortex shedding or passive and active flutter systems (usually hydrofoils) that induce mechanical oscillations in a direction transverse to the water flow. Most of these devices are in the conceptual stage of development and have not been evaluated in terms of cost or performance.

6.3.5 Ocean thermal energy conversion

Ocean thermal energy conversion (OTEC) plants are based in three possible types of cycle for the conversion scheme: open, closed and hybrid (Charlier and Justus 1993).

In the open conversion cycle, sea water is used as the circulating fluid and the warm surface water is flash evaporated in a partial vacuum chamber. The produced steam passes through a turbine, generating electricity, before which it is cooled in a condenser by using cool water pumped from the sea bottom. Using a surface condenser, desalinated water is obtained as an additional output.

Closed conversion cycle is believed to present the best solution in terms of thermal performance. A secondary working fluid, such as ammonia, propane or Freon-type is vaporized and re-condensed continuously in a closed loop to drive a turbine. Warm sea water from the ocean surface is pumped through heat exchangers where the secondary working fluid is vaporized, causing a high pressure vapor to drive a turbine. The vapor flows to a surface condenser to return to the liquid phase, cooled by cool sea water. In the closed cycle turbines are reduced in size compared with open cycle turbines, because of the higher operating pressure associated with the secondary working fluid. A schematic OTEC closed conversion cycle is shown in Figure 6.18.

The hybrid conversion cycle combines both open and closed cycles. Steam is generated by flash evaporation and then acts as the heat source for a closed Rankine cycle, using ammonia or other working fluid.

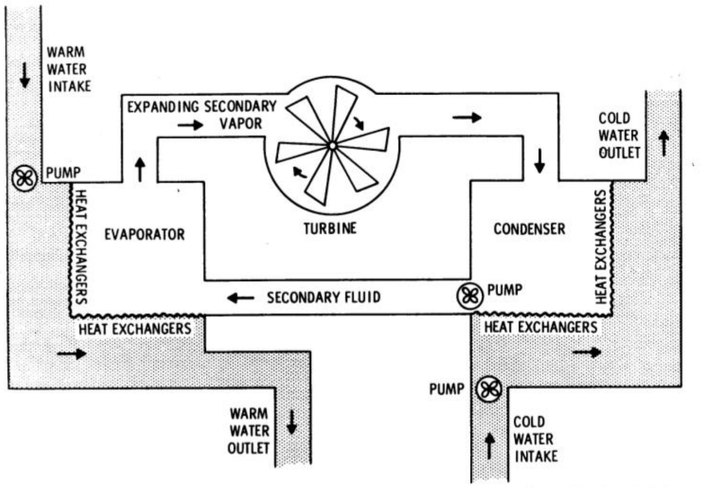


Figure 6.18 : Diagram of a closed cycle OTEC plant , National Science Foundation (Charlier and Justus, 1993).

6.3.6 Salinity Gradient

It has been known for centuries that the mixing of freshwater and seawater releases energy and so a river flowing into a saline ocean releases large amounts of energy (Wick and Schmitt, 1977). The challenge is to utilise this energy, since the energy released from this mixing normally results in a very small increase in the local temperature of the water. During the last few decades at least two concepts for converting this energy into electricity instead of heat have been identified, these are Reversed Electro Dialysis (RED) and Pressure Retarded Osmosis (PRO).

[TSU: Use of level 4 subheadings?]

The Reversed Electro Dialysis (RED) process is a concept where the difference in chemical potential between two solutions is the driving force. To utilise this concept, the concentrated salt solution and freshwater are brought into contact through an alternating series of anion and cation exchange membranes as shown in Figure 6.19.

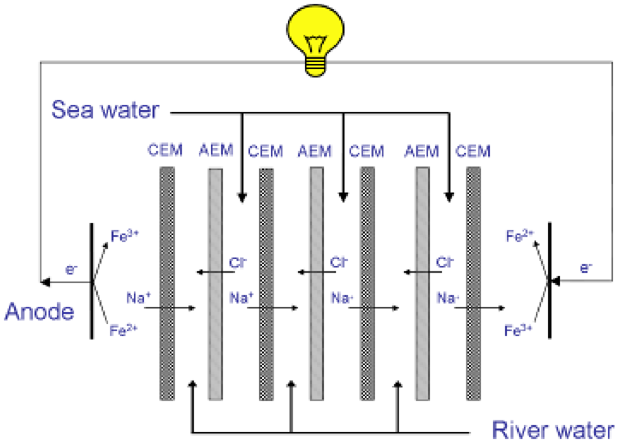


Figure 6.19: Reversed Electro Dialysis (RED) [TSU: Please add source.]

The chemical potential difference generates a voltage over each membrane and the overall potential of the system is the sum of the potential differences over the sum of the membranes. This concept is under development in the Netherlands and there are preparations for the first prototype to be built (Groeman and van den Ende, 2007).

Pressure Retarded Osmosis (PRO), also known as Osmotic Power, is a process where the chemical potential is exploited as pressure as shown in Figure 6.20. This was first considered by Professor Sidney Loeb in the early 1970s (Loeb and Norman, 1975).

The osmotic power process utilises naturally occurring osmosis, caused by the difference in concentration of salt between two liquids (for example, sea water and fresh water). Sea water and fresh water have a strong force towards mixing, and this will occur as long as the pressure difference between the liquids is less than the osmotic pressure difference. For seawater and freshwater this will be in the range of 24 to 26 bars, depending on the salt concentration of seawater.

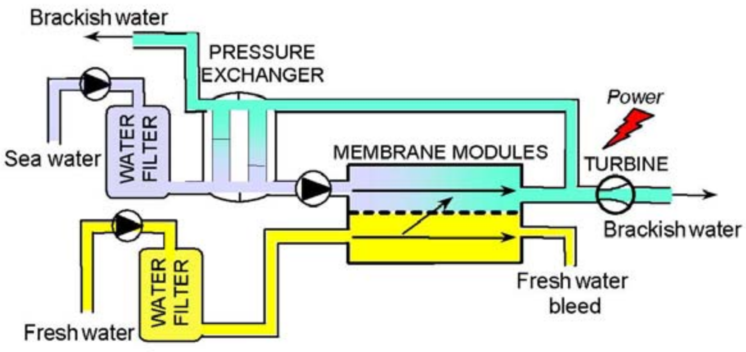


Figure 6.20: Pressure Retarded Osmosis (PRO) process (Scråmestø, Skilhagen and Nielsen, 2009).

In a PRO system filtered fresh water and sea water are fed into the system. Before entering the membrane modules, the seawater is pressurized to approximately half the osmotic pressure, about 12 - 13 bars. In the module freshwater migrates through the membrane and into pressurized seawater. This results in an excess of diluted and pressurised seawater (brackish water), which is then split in two streams. One third is used for power generation (corresponding to approximately the volume of freshwater passing through the membrane) in a hydropower turbine, and the remaining part passes through a pressure exchanger in order to pressurize the incoming seawater. The effluent from a plant will be principally brackish water, which can be fed back to the river or into the sea, where the two original sources would have eventually mixed.

6.4 Global and Regional Status of Markets and Industry Development

6.4.1 Introduction

Presently, the only commercial ocean energy technology available is the tidal barrage, of which the best example is the La Rance Barrage in northern France. Tidal barrages effectively use conventional hydroelectric generating equipment but extract power from tidal flows in estuarine environments. Tidal barrages are usually large, very capital-intensive constructions, which require other uses to justify development. These other uses may include communication access, facilitating regional development, such as at the La Rance project in northern France or alleviation of environmental problems, such as at Sihwa in Korea.

Although some wave and tidal current devices are approaching commercial development, other technologies to develop the other ocean energy sources - ocean thermal energy conversion (OTEC), salinity gradients, ocean currents, submarine geothermal and marine biomass - are still at conceptual or early prototype stages.

Khan and Bhuyan (2009) reviewed the number of ocean energy systems under development so far. What is telling is not only the number of developments but the geographic dispersion of these projects (Figure 6.21).

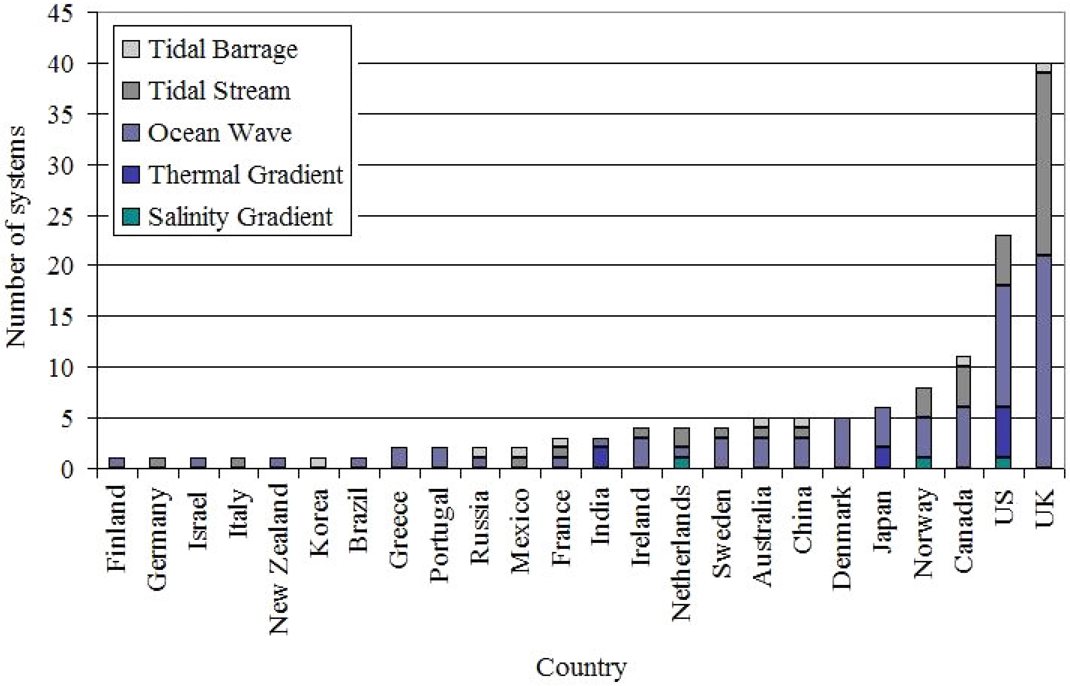


Figure 6.21: Country participation in ocean energy conversion system development (courtesy Khan and Bhuyan, 2009).

6.4.1.1 Markets

Apart from tidal barrages, all ocean energy technologies are conceptual, under research and development or at best have reached pre-commercial prototype stage. Consequently, there is no commercial market for ocean energy technologies at present. Some governments, such as the United Kingdom, Scottish Executive and others promote prototype device deployments through special funds (the Marine Renewables Deployment Fund - MRDF in the UK and the Wave and Tidal Energy Scheme - WATES in Scotland). Others are trying to accelerate market acceptance of ocean energy technologies through the use of renewables obligations or renewable portfolio standards, under which generators must supply electricity from specific technologies, such as ocean energy, or pay a penalty, which is then recycled by the government to promote the development of that technology, e.g. feed-in tariffs for ocean-generated energy introduced in Ireland and Portugal.. The United Kingdom and Scotland have such schemes. The Scottish Executive has introduced a prize, called the Saltire Prize, for the development of the first marine energy technology that meets a continuous generation target.

From a regional perspective it would be reasonable to suggest that the United Kingdom, Ireland and other north-eastern [TSU: "NE" replaced by "north-eastern".] Atlantic coastal countries lead the development of a market for ocean energy technologies and their produced electricity.

Funding mechanisms such as the Clean Development Mechanism (CDM) or Joint Implementation (JI) projects are ways in which governments can secure additional external funding for the development of tidal barrages or other ocean energy projects. The Sihwa barrage project in the Republic of Korea, which is expected to commence operations in 2010, was funded in part by CDM finance.

The introduction of emissions trading schemes and/or carbon taxes to promote emissions reductions may also promote uptake of ocean energy technologies, by effectively pricing in the cost of CO_2 emissions, which will advantage renewable technologies, such as wave and tidal stream technologies, which produce no emissions in operation.

6.4.1.2 Industry Development

Industrial development of ocean energy is at a very early stage. There is no true manufacturing industry for ocean energy technologies at present but the growth of interest may lead to the development of new skills and capabilities. Whilst there is little or no capacity in the present marine energy supply chains, redirection of capacity and expertise from existing industries, such as electrical and marine engineering and offshore operations, could lead to rapid growth of supply chains for technology development and manufacturing and deployment projects.

Development of industries will depend on early uptake and support by governments and may thus be regional, rather than global. As noted the north-eastern [TSU: "NE" replaced by "north-eastern".] Atlantic coastal countries from the UK to Portugal are leading developments of technologies and markets. This results from governments in these countries supporting new industry through R&D grants, capital grants for deployments, regional support initiatives for cluster developments and supply obligations for generating companies (see section 6.4.7). These countries have begun to assess the market potential for ocean energy as an industry development or regional development initiative. Industry development road maps and supply chain studies have been developed for Scotland, the United Kingdom and New Zealand (FREDS, 2009; UKERC, 2008; AWATEA, 2008).

There are now a series of global and regional initiatives for collaborative development of ocean energy markets and industry. These are assisting in the development of international networks, information flow, removal of barriers and efforts to accelerate marine energy uptake. The presently active initiatives include the following:

1) International Energy Agency's Ocean Energy Systems Implementing Agreement

2) EquiMar – the Equitable Testing and Evaluation of Marine Energy Extraction Devices (a European Union-funded initiative to deliver a suite of protocols for evaluation of wave and tidal stream energy converters)

3) WavePLAM – the WAVe Energy PLanning And Marketing project (a European industry initiative to address non-technical barriers to wave energy).

[TSU: website links as footnotes to the above mentioned initiatives?]

6.4.2 Wave Energy

Wave energy technologies started to be developed with appropriate scientific basis after the first oil crisis in 1974. Many different converter types have been and continue to be proposed and tested but we are still at the beginning of pre-commercial phase. It is usual to test devices at small-scale in laboratory test-tank facilities (~1:100) before the first open-sea prototype testing (1:10 – 1:4 scale). Pre-commercial testing may be at 1:2 or 1:1 scale before the final full-scale commercial version becomes commercially available. Presently only a handful of devices have been built and tested at full-scale and none are truly commercial.

A coast-attached oscillating water column device has been occasionally operational in Portugal since 1999 and a somewhat similar device (Wavegen’s LIMPET device) has been operating almost continuously on the island of Islay in Scotland since 2000. Offshore oscillating water column devices have been tested at prototype scale in Australia (Energetech/Oceanlinx) since 2006 and Ireland (OE Buoy) since 2007.

The most advanced oscillating-body device is the 750 kW Pelamis Wavepower attenuator devices, which has been tested in Scotland and deployed in Portugal. The Portuguese devices were sold as part of a commercial project. The company is currently building its next commercial device. The other near-commercial oscillating-body technology is the Ocean Power Technologies’ PowerBuoy, a small (40 – 150 kW) vertical axis device, which has been deployed in Hawaii, the US eastern seaboard and off the north Spanish coast. Other oscillating-body devices under development include the Irish device, Wavebob, and the Wave Energy Technology-New Zealand device.

Two Danish overtopping devices have been built at prototype-scale (Wave Dragon and WavePlane).

[TSU: website links as footnotes to the above mentioned devices (marked yellow)?]

6.4.3 Tide Rise and Fall

Presently, only estuary-type tidal power stations are in operation. They rely on a barrage, equipped with generating units, closing the estuary.

The only industrial-scale tidal power station in operation in the world to date is the 240 MW La Rance power station which has been in successful operation since 1966. Other smaller projects have been commissioned since then in China, Canada, Russia (Figure 6.22).

The conversion mechanism most widely used to produce electricity from tidal rise and fall is the ‘bulb-type’ unit (Figure 6.13). This technology was first developed in France for an application at the La Rance tidal power station near St. Malo, which was commissioned in 1966 with 24 x 10 MW units. Since 1997 these turbines have operated on both the ebb and flood tide.

The 254 MW Sihwa barrage (South Korea) is expected to be commissioned in 2010 and will then become the largest tidal power station in the world. Sihwa power station is being retro-fitted to an existing 12.7 km sea dyke that was built in 1994. The project will, when operational, generate electricity, while also improving flushing the reservoir basin to improve water quality.

By the end of 2010, the world's installed capacity of tidal rise and fall will still be less than 600 MW, Figure 6.22.

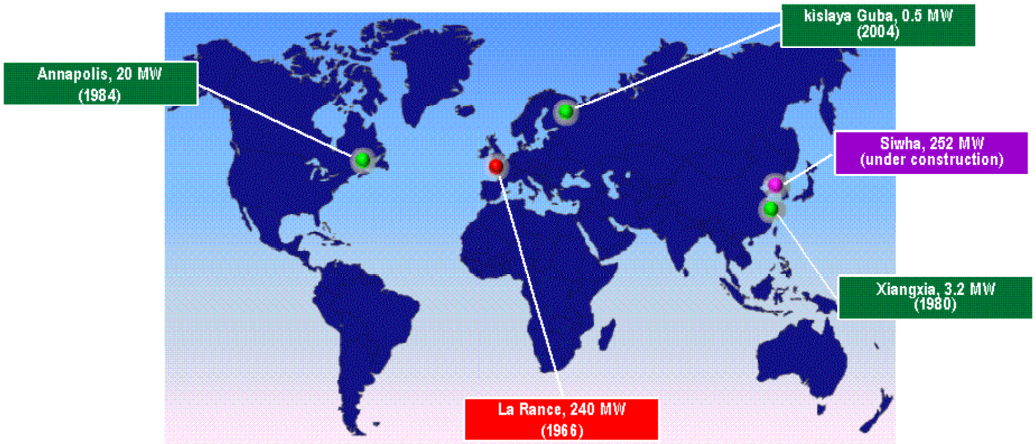


Figure 6.22: Tidal rise and fall power station in operation as of March 2009 (courtesy EDF) [TSU: status of source?]

However, numerous projects have been identified, some of them with very large capacities. Some are of the estuary type, some rely on the new offshore or coastal basin concept, Figure 6.23.

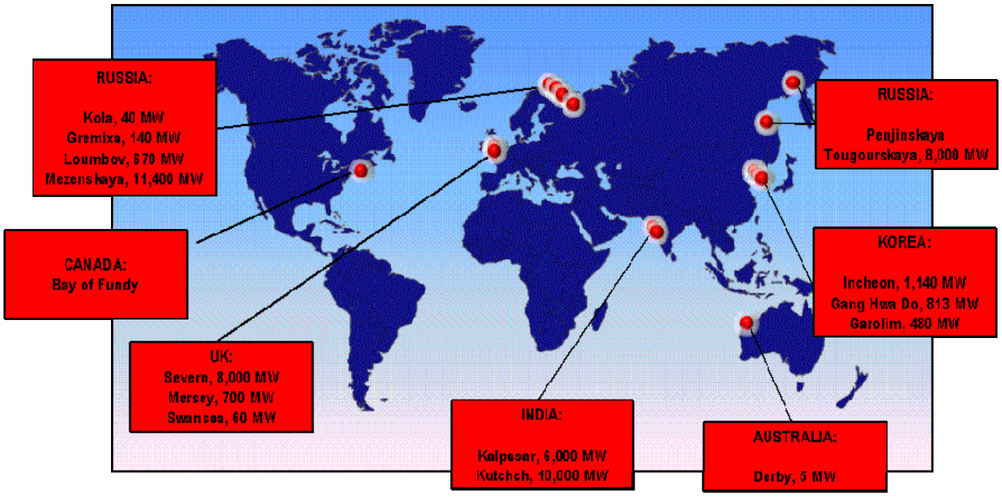


Figure 6.23: Tidal rise and fall power station planned as of March 2009 (courtesy of EDF) [TSU: status of source?]

6.4.4 Tidal and Ocean Currents

All tidal stream energy systems are in the proof of concept or prototype development stage, so large-scale deployment costs are not yet known. The most advanced example is the SeaGen tidal turbine, which was installed in Strangford Lough in Northern Ireland. This is now an accredited 'power station' but there are competitors so far advanced, it is not yet known what the true market potential is. Most of these projections should be based on the available resources referenced in Section 6.2. From the global surveys, the best markets for tidal energy are in United Kingdom, USA, Canada, northeast [TSU: "NE" replaced by "northeast".] Asia, and Scandinavia (EDF, 2009).

Tidal energy has some unique attributes that may enhance its market value. Tidal stream flows are often located near population centres, where the electricity delivery is not constrained by the further requirement for long transmission lines. They have a very low visual impact, so in this regard they can also be located close to populations. Tidal flows are also very predictable, which is extremely valuable in utility generation planning and forecasting.

Generally, the resource for tidal energy is not widespread and tends to be located in specific sites where the current velocities are high enough for economic viability. The threshold for this velocity is thought to be at least 1 m/s but not enough is known about costs and this value may vary as technology improvements are introduced. Generally, the global resource and hence, markets, must be large enough to support enough deployment and experience for the technology to reach commercial maturity. International collaborations and collaborations among tidal, river, and ocean current technology sub-sectors will be essential to achieve necessary market acceleration and cost reductions.

Open ocean currents, such as the Gulf Stream, are being explored for their potential. Unlike tidal stream flows, ocean currents tend to be slower, unidirectional but involve much larger bodies of water. Harnessing open ocean currents may require different technologies from those presently being developed for the faster, more restricted tidal stream currents (MMS, 2006).

6.4.5 Ocean thermal energy conversion

Two floating ocean thermal energy conversion (OTEC) plants have been built in India. In 2005, a short 10-day experiment was conducted using an OTEC system mounted on a barge near Tuticorin (Ravindran, 2007). A barge was moored in water 400 m deep, and at one point successfully produced fresh water at a rate of 100,000 liters per day. The design for this barge was created in co-operation with Saga University of Japan, and used a closed cycle system, with ammonia as a working fluid. The design, which was originally from 1984, was rated at 1 MW and apparently began construction in 2000; however, some equipment was lost due to various problems during implementation. It is unclear whether the 2005 barge was capable of power production and whether it was still based on a closed-cycle design. Another barge, which is intended for long-term production, is moored in water 1 km deep near Chennai and has its cold-water intake pipe at a depth of 500m. The barge can produce one million liters of fresh water per day, however, rather than generate power it currently uses diesel generators to power the pumps.

In 2005, a land-based plant, capable of producing 100,000 liters per day of freshwater was built on the island of Kavaratti, using a cold-water intake pipe mounted 350 m deep in the ocean (National Institute of Ocean Technology, 2007). The location offered access to water at 400 m depth only 400 m from shore, making it an ideal site for OTEC. The current plant does not incorporate electrical generation.

A small OTEC demonstration plant, called Mini-OTEC, was built in US in 1979 (Vega, 1999). The plant was built on a floating barge, and used an ammonia-based closed cycle system. The 28,200 rpm radial inflow turbine gave the prototype a rated capacity of 53 kW; however, efficiency problems with the pumps allowed it to generate only 18 kW. One year later, another floating OTEC plant, called OTEC-1, was built. It used the same closed-cycle system and was rated at 1 MW; however, it was primarily used for testing and demonstration and did not incorporate a turbine. It was operational for four months during 1981, during which time issues with the heat exchanger and water pipe were studied.

During 1992, an open-cycle OTEC plant was built in Hawaii (Ocean Thermal Energy, 2007). It operated from 1993 to 1998, and it had a rated capacity of 255 kW. Peak production was 103 kW and 0.4 L/s of desalinated water. Various difficulties with the technology were encountered, including problems with out-gassing of the seawater in the vacuum chamber, the vacuum pump itself, and varying output from the turbine/generator.

Several OTEC power plants have been built in Japan (Kobayashi et al., 2004). A 120 kW plant was built in the republic of Nauru, which used a closed cycle system based on Freon and a cold water pipe with a depth of 580 m. The plant operated for several months and was connected to the power grid; it produced a peak of 31.5 kW of power. Several smaller closed-cycle plants were also constructed in the following years, but were not kept operational long-term. The Institute of Ocean Energy (IOES) at Saga University / Japan created a small-scale 30 kW Hybrid OTEC plant during 2006. The prototype was based on a mixed water/ammonia working fluid, and was able to successfully generate electrical power.

Sea Solar Power is developing a hybrid closed-cycle/open cycle OTEC system (Sea Solar Power, 2007). The design calls for the use of a propylene-based closed cycle system, providing 10 MW of power in a shore-based plant or 100 MW in an offshore one. Along with the closed-cycle electrical generation system, an open-cycle system will be run in parallel to provide fresh water and additional generation. Although concept designs of the plants have been created, it is unclear if any development is still occurring.

6.4.6 Salinity Gradient

[TSU: sources missing.]

Osmotic power is still a concept under development. Utility sector and research groups initiated early development of osmotic power systems but, more recently, new groups have become engaged as the industry emerges. The parallel development in related technologies, such as desalination, will benefit the osmotic power industry.

In addition several governments and organisations have already engaged in both supporting the development itself and consideration of necessary instruments to bring this source of renewable energy to the market.

6.4.7 Ocean Energy-Specific Policies

Because ocean energy technologies are relatively new but offer the opportunity for yet another GHG-free electricity- and water-generation technology, numerous governments have introduced policy initiatives to promote and accelerate the uptake of marine energy. These policies range from funding initiatives, incentives to specifically promote marine energy deployments and other regulatory initiatives to reward developers of marine energy technologies and deployment projects.

There are now too many initiatives to list fully, so the following table gives well-established examples of such policy settings (Table 6.2). Policies fall into four categories:

- Targets for installed capacity or contribution to future supply
- Capital grants and financial incentives, including prizes
- Research and testing facilities and infrastructure
- Permitting/space/resource allocation regimes, standards and protocols

It is notable that most of the countries that have ocean energy-specific polices are those that are most advanced with respect to technology developments and deployments. Government support for ocean energy is critical to the pace at which ocean energy is developed.

There are a variety of targets both aspirational and legislated. Most OE-specific [TSU: chapter-specific abbreviations, OE: ocean-energy.] targets relate to proposed ocean energy installed capacity targets. These specific targets complement other targets – for percentage increases of renewable energy generation or renewably generated electricity.

Most countries offer R&D grants for renewable energy technologies but some have ocean energy-specific grant programs. The United Kingdom and, since 2008, the United States have the largest and most sophisticated programs. Capital grant programs for device deployments have been implemented by both the United Kingdom and New Zealand as ‘technology push’ mechanisms.

Some European countries, such as Portugal, Ireland and Germany, have preferred ‘market pull’ mechanisms, such as feed-in tariffs (i.e. performance incentives for produced electricity from specific technologies). The United Kingdom has a Renewable Obligations Certificates (ROCs) scheme, i.e. tradable certificates awarded to generators of electricity using ocean energy technologies. More recently the Scottish Executive has introduced the Saltire Prize, a prize for the first device developer to meet a cumulative electricity generation target.

Table 6.2: Examples of Ocean Energy-Specific Policies [TSU: Please add source.]

Policy Instrument	Country	Example Description
Aspirational Targets and Forecasts	United Kingdom Basque Country, Spain	3% of UK electricity from ocean energy by 2020 5 MW off Basque coast by 2020
Legislated Targets (total energy or electricity)	Ireland Portugal	Specific targets for marine energy installations 500 MW by 2020 550 MW by 2020
R&D programs/grants	United States	US DoE Hydrokinetic Program (capital grants for R&D and market acceleration)
Prototype Deployment Capital Grants	United Kingdom New Zealand	Marine Renewables Proving Fund (MRPF) Marine Energy Deployment Fund (MEDF)
Project Deployment Capital Grants	United Kingdom	Marine Renewables Deployment Fund (MRDF)
Feed-in Tariffs	Portugal Ireland/Germany	Guaranteed price (in $/kWh or equivalent) for ocean energy-generated electricity
Renewables Obligations	United Kingdom	ROCs scheme (tradable certificates (in $/MWh or equivalent) for ocean energy-generated electricity
Prizes	Scotland	E.g. Saltire Prize (GBP 10 million for first ocean energy device to deliver over 100 GWh of electricity over a continuous 2-year period)
Industry association support	Ireland New Zealand	Government financial support for establishment of industry associations
National Marine Energy Centres	United States	Two centres established (Oregon/Washington for wave/tidal & Hawaii for OTEC)
Marine Energy Testing Centres	Most W. European and N. American countries	E.g. European Marine Energy Centre; there are c. 14 centres under development worldwide
Offshore Hubs	United Kingdom	E.g. wave hub, connection infrastructure for devices
Standards/protocols	United Kingdom	National standards for ocean energy (as well as participation in development of international standards)
Permitting Regimes	United Kingdom	Crown Estate competitive tender for Pentland Firth licences
Space/resource allocation regimes	United States	FERC/MMS permitting regime in US Outer Continental Shelf

6.5 Environmental and Social Impacts

[TSU: references missing.]

6.5.1 Introduction

All renewable energy projects will produce positive and negative environmental and social impacts. Since all ocean energy devices produce no CO_2 during operations, they must be accounted attractive for climate change mitigation purposes. Positive effects include strengthening of regional energy supply, regional economic growth, employment and eco-tourism. Negative effects may include reduction in visual amenity, loss of access to space for competing users, such as fishing and navigation. The effects of each ocean energy projects will be different both on the environment in which they are located and on the communities that live near them or benefit from their products. Projects under construction will have different effects than projects in operation. Although most ocean energy projects are likely to be long-lived (25 – 100 years), the lasting effects of their development will be important. There is a growing environmental concept: reversibility, which considers that any project development should be reversible without any long-term or permanent effects.

Wave devices are unlikely to produce too many environmental effects. Offshore wave devices themselves must, at least partially, float in the water column in a very energetic environment. The key potential environmental effects will be loss of space around the deployment site for other uses, including fishing and navigation. Moorings on the seabed may affect both benthic and pelagic species and concern is frequently expressed about the potential collision risk for marine mammals and cetaceans. However, this risk is currently unrealized and may be very small. The absence of any significant noise or visual impacts is a benefit to wave devices.

Tidal barrages are usually located in estuaries, which are complex, dynamic and potentially fragile environments. Further a barrage is a massive construction and not easily removed. This problem, also faced by coast-attached wave energy devices, may face the challenge of reversibility. Tidal stream devices may benefit from having little irreversible effects. Like wave energy devices, tidal stream devices will be located mainly in the water column and in a very energetic environment. Apart from the effects of moorings on the seabed and benthic fauna and competition for space, there may be little long-term effects of a tidal energy project.

The principal environmental impacts of both ocean energy thermal conversion (OTEC) and salinity gradient projects will be the outflow of significant quantities of exotic cold water (OTEC) and brackish water (salinity) from these plants.

The general concerns comprise the effect of deployment, operation and maintenance (O&M) and decommissioning on local flora and fauna, and to a certain extent also the alteration of the physical environment. Noise impact is another issue. In addition, cabling the power generated to shore will involve bottom disturbances, including electromagnetic field hazards for some species.

Increasingly governments are undertaking Strategic Environmental Assessments (SEAs) to assess and plan for potential environmental effects of ocean energy projects.

An ocean power station of any type becomes a source of eco-tourism and attraction in its own right, providing jobs in tourism and services. Any type of ocean energy development will require extensive social and environmental impact assessments to fully evaluate all development options. A continuing program of public and stakeholder engagement is necessary to ensure that the concerns of various parties are duly considered in the development and operation of any project.

Social benefits may be national – creation of new industries, redirection of resources from declining industries, developments of regional clusters, whilst individuals may benefit from new employment opportunities, training for new skills and development of new capabilities.

6.5.2 Wave Energy

The public perception of the importance of environmental impacts of wave energy technologies comes from the lack of deployment experience with various wave energy conversion technologies. Good projections can be made using data from other offshore technologies, such as oil and gas and offshore wind. The potential impacts on the marine environment can be expected to be similar in many aspects to those of offshore wind turbines, which have now been monitored for several years. The potential effects on bird migration routes, feeding and nesting will not be relevant in this case, and visual impacts of marine energy converters should be negligible, except large arrays of devices located nearshore.

The following impacts on the biosphere in the vicinity of the converters are of concern: infauna (aquatic animals that live within the bottom substratum rather than on its surface) and hard bottom substrate; fish habitat, communication and orientation, marine mammal behavior and orientation.

The potential impact of electromagnetic fields around devices and electrical export cables that connect wave farms to the mainland electrical grid is an important issue that has been investigated for offshore wind farms. These effects are expected to be relevant to sharks and rays that use electromagnetic impulses to navigate and find prey. Another important impact is chemical footprint due to accidents (e.g. oil leaks from hydraulic power-take-off systems (PTO)) and abrasion (paints and anti-fouling chemicals).

Noise is one of the potentially most important impacts that needs investigation. It can be emitted during deployment and decommissioning and during operation, at frequencies that depend on the PTO.

Energy capture and thus downstream effects on wave height are a potential concern of surfing communities. They fear that wave energy farms will reduce swell conditions at adjacent beaches. This can be assessed through numerical and tank testing studies.

Regarding the socio-economic impacts it is expected that the large-scale implementation of wave farms will have positive impacts at general and local levels. In addition to electricity generation with rather small lifecycle greenhouse gases emission, it will decrease the import of fossil fuels (in those countries that do not possess such fuels) and will increase the local work of shipyards (devices construction and/or assembling), transportation, installation and maintenance. However there can be a number of conflicts of interest namely with fishing industry leading to some potentially negative socio-economical impacts (loss of income for local fishing industry) or just a change in methods (trawling will be impossible in the wave energy farms area). However, installation of a wave device array may cause general better use of fish resources whose stocks has decreased to dangerous levels due to overfishing in the last decades.

6.5.3 Tide Rise and Fall

Development of tidal rise and fall power projects are often considered as local or regional development projects. They always produce impacts, positive and negative, on the natural environment and on the local economy, whether they are barrages across natural estuaries or stand-alone offshore impoundments (i.e. tidal lagoons).

Estuaries are complex, unique and dynamic natural environments, which require very specific and careful attention. The impacts on the natural environment have to be addressed for both the construction phase and for future operations. For an estuary-type project, construction impacts will differ depending on the construction techniques employed: a total closure of the estuary during the construction period will affect fish life and biodiversity in the estuary whereas other methods such as floating caissons sunk in place for example will be less harmful.

At the La Rance project, although the estuary was closed for the construction period, biodiversity comparable to that of neighboring estuaries was restored less than 10 years after commissioning, thanks to the responsible operating mode at the power station. The environmental impacts during construction of the Sihwa project have been very limited since the barrage already existed.

A barrage will affect the amplitude of the tides inside the basin and therefore modify both fish and bird life and habitat, water salinity and sediment movements in the estuary. The need to ensure a minimum head between the basin and the sea will also lengthen the flat times in the basin at high and low tides.

A sound operational methodology is thus critical to mitigate the environmental impacts in the estuaries. In La Rance, two tides a day are systematically maintained by the operator inside the basin, which has resulted in the rapid restoration of a “natural” biodiversity in the basin. However, it is noticeable that sediments are accumulating towards the upstream end of the basin, requiring regular and costly dredging operations.

Offshore tidal lagoons do not produce the same type of negative impacts. Being located offshore they do not have any impact on delicate nearshore ecosystems. Obviously they will have an impact on the area covered by the new basin, but provided this area is located away from sea currents, the impacts on marine life and biodiversity may be limited and temporary.

In terms of social impact, projects constructed to date did not require any relocation of nearby inhabitants. This should continue to be so for future projects, as it is unlikely, even in the case of pumping, that the water level in the basin would be substantially higher than the water level at very high tides. Further these basins will be artificial installations at sites not previously inhabited.

Offshore tidal lagoons may have an impact on fishing activities but this impact should be limited, when the projects are located away from sea currents. Lagoons may even be used to develop aquaculture to breed certain species of fish adapted to calm waters.

The construction phase usually requires large numbers of workers for the construction of the civil works, which often represent a significant amount of investment and economic benefit to local communities.

Estuary-type projects are often associated with the creation of new and shorter routes due to the use of the top of the barrage walls as roads linking locations originally with difficult access to each other. This will be positive in terms of improvement of socio-economic conditions for local communities. It should also lead to reductions in CO_2 emissions by reducing travel distances.

6.5.4 Tidal and Ocean Currents

6.5.4.1 Tidal Currents

Tidal current technologies are likely to be large submarine, although some devices have surface-piercing structures. Environmental effects will be somewhat limited because devices are located in an already energetic, moving water environment. A key concern with tidal current technologies is that they have rotating rotor blades or flapping hydrofoils - moving parts, which may harm marine life. To date there is no evidence of harm to marine life (such as whales, dolphins and sharks) from tidal current devices and this may in part be due to slow rotation speeds (relative to escape velocities of the marine fauna) and the passive nature of the rotating device. Substantial research is under way to establish likely environmental effects and mitigation strategies.

Another potentially serious effect will be on fishing, particularly trawling, which will clearly be banned near submarine rotating equipment. Accommodations with present commercial, recreational and customary fishing activities will be required. On the positive side, arrays of tidal current turbines may act as de facto marine reserves, effectively creating new but protected habitats for some marine life.

6.5.4.2 Ocean Currents

Full scale commercial deployments of open-ocean current electric generating systems could present certain environmental risks (Charlier, 1993; Van Walsum, 2003). These can be grouped into four broad categories: the physical environment (the ocean itself), benthic (ocean-bottom) communities, marine life in the water column, and commerce. None of these has been fully explored in the literature.

Ocean current systems, which have sufficient velocities to be cost-effective, are all associated with wind-driven circulation systems, and generation devices will not alter this circulation or its net mass transport. For example, the equator-ward sverdrup drift in the wind-driven circulation, for which western boundary currents are the poleward return flow, is independent of the basin's dissipative mechanisms (e.g. Stommel, 1966). There could, however, be alterations in the patterns of meandering and in upper-ocean mixing processes, because the characteristics of the boundary current do depend on dissipation. The impacts of these effects need to be fully evaluated prior to full site development. In the case of the Atlantic Ocean’s Florida Current, modelling studies using the HYCOM high-resolution regional simulation capability are underway to assess these potential impacts (e.g. Chassignet et al., 2009).

Because open-ocean deployments will require mooring systems, benthic communities will be affected – potentially both adversely and positively – by anchor emplacement. While many sites are sufficiently deep that, generally, these potential impacts are not likely to be an issue, the deep-water coral communities off the coast of Florida may be vulnerable and will be carefully monitored for impacts during early deployments.

Open-ocean generating systems will operate at depths below the draft of even the largest surface vessels so hazards to commercial navigation will be minimal. Undersea naval operations could be impacted, although the stationary nature of the systems will make avoidance relatively simple. Of more potential impact is the fish habitat that may be created in association with the underwater structures and its attraction to sports fishing. Because underwater structures are known by marine scientists and recreational fishers to become fish aggregating devices (FAD) (Relini et al., 2000), possible user conflicts, including line entanglement issues, must be considered. Associated alterations to pelagic habitats, particularly for large-scale installations, may become issues as well (e.g. Battin, 2004).

6.5.5 Ocean thermal energy conversion

The four main sources of environmental concerns associated with deployment and operations of ocean thermal energy conversion (OTEC) plants are (Charlier and Justus, 1993):

(a) Redistribution of oceanic properties: ocean water mixing, impingement/entrainment, climate/thermal;

(b) Chemical pollutions: biocides,working fluid leaks, corrosion;

(c) Structural effects: artificial reef, nesting/migration;

(d) Socio-legal economic: worker safety, enviro-maritime law, secondary economic impact.

Potential changes in the oceanographic properties of sea water due to OTEC pumping operations are a major environmental concern. Considering that large amounts of cold deep water and warm shallow water will be pumped to the heat exchangers, parameters such as temperature, salinity, density, dissolved oxygen, nutrients, carbonates etc will be modified by mixing with ambient ocean water in the vicinity of the eventual discharge.

Under normal operating conditions, OTEC power plants will release few emissions to the atmosphere and will not adversely affect local air quality. The magnitude of possible climatic effects resulting from sea-surface temperature alterations by commercial OTEC development have not yet been ascertained and additional research on this theme is recommended.

6.5.6 Salinity Gradient

Mixing of seawater and freshwater is a natural process that occurs all over the world. An osmotic power plant will extract the energy using this process without any significant interference with the environmental qualities of the site. Freshwater and seawater mixed in an osmotic power plant will be returned (to the sea) as brackish water, where they would have eventually mixed naturally. The other outputs of the process produce no significant effluents that could interfere with the global climate. Like other renewable energy sources, osmotic power will not produce any operational CO_2 emissions.

Assessments of the environmental optimisation and pre-environmental impact of an osmotic power plant located at a deltaic/estuarine river mouth have not identified any serious obstacles. Major cities and industrial area are often sited at the mouths of major rivers, so osmotic power plants need not be constructed in unspoilt areas. The plants can be constructed partly or completely underground to reduce their environmental footprint on the local environment. Onshore environmental impacts are likely to be limited to such aspects as construction of electricity connections, access roads, etc.

Although there are few known environmental impacts, this will be carefully monitored as the industry develops. Water take will need to be monitored to ensure that water is not extracted in low flow conditions. Brackish water is the main waste product of osmotic power and the discharge of brackish water into the marine environment may alter the environment and result in changes for animals and plants living in the local location. The impact of produced brackish water on the local marine environment will need to be monitored. Deltaic/estuarine environments are notably sensitive to changes in water level and pollution so baseline studies and operational monitoring will be required.

Developed areas, such as cities, may have already affected the river mouth adversely. Careful and controlled building of the plant inlet, osmotic power plant and outlet could improve the present condition of biotopes of the river, the estuary and the sea.

6.6 Prospects for Technology Improvement, Innovation and Integration

[TSU: references missing.]

6.6.1 Wave Energy

Wave energy technologies are still largely at a very nascent stage of development and all are pre-commercial. Any cost or reliability projections are speculative with a high level of uncertainty because they require assumptions to be made about optimized systems that have not yet been proven at or beyond the prototype level. Nevertheless, a priority for the wave device developers is to gain enough operating experience on early devices so that engineering practices and technology development can advance. Wave energy devices are likely to follow a long-term development path which allows scaling to the largest practical machine size to minimize the number of operation and maintenance (O&M) service visits, lower installation and decommissioning costs, and reduce mooring requirements, similar to the wind energy industries progression to larger rotors. Maximizing energy production will play a large part in the overall cost reduction of wave energy systems. This will depend on building efficient capture devices as well as dependable and efficient conversion systems. Performance and reliability will be top priorities for wave energy systems as commercialization and economic viability will depend on systems that require little servicing and can continue to produce energy reliably with minimal maintenance.

6.6.2 Tide Rise and Fall

Tidal rise and fall power projects rely on proven technologies in civil and electromechanical engineering, albeit built and operated in an estuarine rather than a riverine environment.

There are basically three areas where construction improvements can still be achieved. Firstly, in the design of the facilities, very large offshore facilities will allow the development of cost effective projects. Secondly, the use of multiple basins will increase the value of projects by reducing the intermittency of generation, thus allowing a better placement of the energy generated on the load curve. Thirdly, in terms of electromechanical equipment, general turbine efficiency and, more specifically, the ability to improve generation efficiency in both flow directions are future challenges that will be determinant on the future of tidal rise and fall hydropower. The turbines should have the ability to operate both ways and the units should preferably operate as well as pumps. Such equipment has been used successfully for 40 years at La Rance in France. Technologies may be further improved, for instance, with gears allowing different rotation speeds for the turbine and the generator or with variable frequency generation, allowing better outputs for the various operating ways and heads.

As regards civil works, power plants may be built in situ within cofferdams or pre-fabricated in caissons (steel or reinforced concrete) and floated to site. The caisson solution is particularly adapted to remote sites: caissons with several turbine bays totalling 200 MW may be used.

6.6.3 Tidal and Ocean Currents

Like wave energy, tidal current technologies are in an early stage of development. All technologies are pre-commercial, so cost and reliability projections are speculative with a high level of uncertainty, because assumptions must be made about optimized systems that have not yet been proven at the prototype level. Extensive operational experience with horizontal axis wind turbines, may provide axial flow water current turbines with a developmental advantage, since the operating principles are fairly well known. As with wave energy technologies a high priority for tidal turbines is to gain operating experience to advance engineering practices and technology development. A premium should be placed on building reliable prototypes that can be studied and improved on the basis of technology, environmental impacts, cost, and reliability. Water current designs are likely to increase swept area (i.e. rotor diameter) to the largest practical machine size to minimize the number of O&M service visits, lower installation and decommissioning costs, and reduce substructure requirements (as happened with wind turbine technologies.

Tidal device performance may be limited by the geometry of the specific channel transect dimensions, constrained by navigational requirements that limit their distance below the surface. To date, assessments of the tidal current energy resources have been predominantly made on a site-specific basis but the total resource could be much larger, if lower current velocities can be considered for device deployments. If significant lower velocity sites exist, tidal device optimization may follow a path toward larger turbines in lower flow regimes. A similar trend is well documented in the wind energy industry in the United States, where wind turbine technology developments targeted less energetic sites in order to gain access to a 20-fold increase in the available resource.

As with wave energy, performance and reliability will be top priorities for future tidal energy systems as commercialization and economic viability will depend on systems that need little servicing, which can continue to produce energy reliably without costly maintenance. To accelerate this maturity and promote reliable systems, new materials to resist degradation caused by corrosion, cavitation, water absorption, and debris impact will be needed. New operating control strategies will be developed to resist extreme loads and mitigate fatigue damage. As environmental impacts become better understood (no significant impacted have been documented to date), tidal turbines will incorporate mitigation systems for the avoidance of these impacts.

6.6.4 Ocean thermal energy conversion

The heat exchanger system is one of the most important components of the closed cycle ocean thermal energy conversion (OTEC) power plants. Evaporator and condenser units must efficiently convert the working fluid from liquid to gaseous phase and back to liquid phase with low temperature differentials. The performance of the thermal conversion cycle is highly dependent on the heat exchangers, their performance causes substantial losses in terms of energy production and therefore the economic viability of the entire OTEC system. Considering that evaporator and condenser units are responsible for 20 - 40% of the plant total cost, most of the research efforts are directed toward some special subjects related to the heat exchanger. In addition to materials selection and design under the operating flow rates, temperatures and pressures, aspects related to biofouling, corrosion and maintenance should be carefully considered (Charlier and Justus (1993).

Marine organisms, mainly plankton and dissolved organic material, will be attracted by the provision of marine nutrients by the OTEC plant. This will stimulate the formation of bacterial slimes and consequent degradation of the heat exchangers performance, unless preventive procedures are implemented.

Special care should be taken in relation to the material to be used for the hest exchanger system. One of the best options is titanium, which resists corrosion. However, due to its high cost, aluminium is an alternative to titanium, if regularly scheduled planned replacement is incorporated in lifetime maintenance activities. Copper-nickel alloys and stainless steel alloys are also candidate materials to be considered in the design stage.

A number of options are available for the working fluid, which has to boil at a low temperature (warm water from surface) and condense at a slightly lower temperature (cold water from deep layers). Three major candidates are ammonia, propane and a commercial refrigerant R-12/31. The main advantages are that it has the highest heat of evaporation and high thermal conductivity, especially in the liquid phase. Non-compatibility with copper alloys should be taken into account during design.

Another important component of an OTEC plant is the large diameter pipe employed to transfer the cold water from deep water to the surface. Experience obtained in the last decade with risers for oil &gas production can be easily transfer to the OTEC plant design.

6.6.5 Salinity Gradient

The World's first osmotic power prototype plant became operational in October 2009 at Tofte, near Oslo in southeastern Norway. The prototype location is within an operational pulp factory, which simplified the approval process and at the same time gives good access to existing infrastructure. The location has sufficient access to seawater and fresh water from a nearby lake (Scråmestø, Skilhagen and Nielsen, 2009).

The main objective of the prototype is to confirm that the designed system can produce power on a reliable 24-hour/day production. After the start-up, initial operation and further testing, experience gained will be based on both operational changes as well as changes to the system and replacement of parts. These changes will be designed to increase the efficiency and optimise power generation. If the results of the prototype and the technology development are as expected, the R&D programme will lead to a commercial technology within a few years.

The plant will be used for further testing of technology developed from parallel research activities to substantially increase the efficiency. These activities will mainly be focussed on membrane modules, pressure exchanger equipment and power generation (i.e. the turbine and generator). There will be a focus on further development of control systems, water pre-treatment equipment, as well as infrastructure around the water inlets and outlets (Scråmestø, Skilhagen and Nielsen, 2009).

6.7 Cost Trends

[TSU: All monetary values provided in this document will be adjusted for inflation/deflation and then converted to US$ for the base year 2005. US$ will be used as standard abbreviation for 2005 United States Dollar throughout the text]

6.7.1 Introduction

It is difficult to accurately assess the economic viability of most ocean energy technologies, because very little experience is available for validation. There are no commercial markets yet to drive marine energy technology development and national policy incentives and government-supported technology R&D are driving most innovation and deployment (US DoE, 2009).

Several studies have been based on extrapolations from prototype cost data (BBV, 2001; Li and Florig, 2006; EPRI, Previsic, 2004 [TSU: Previsic et al., 2004 ?]; Callaghan, 2006; IEA, 2008). These studies make assumptions about key variables, which include:

- total installed capital cost (Capex),
- Reliability (i.e. operations and maintenance (O&M)),
- Performance (energy production)
- Learning curve (total industry wide deployment),
- Economies of scale (project size, production capacity),
- Impact of R&D and value engineering (innovation and implementation)

These studies generally indicate that initial capital costs for marine energy generation can decline to costs achieved by other renewable energy technologies such as wind energy. However, this cost reduction can only be demonstrated theoretically since there are few operating devices and little operating experience. Present capex costs can be determined directly from prototypes in the water but these do not reflect commercial capex costs.

The Carbon Trust reported in 2006 that the prototype and pre-commercial wave energy converters had capex ranging from £4,300/kW (US$7,679/kW) to £9,000/kW (US$16,071/kW) with a midpoint of US$11,875/kW (Callaghan 2006). Similarly they found that prototype tidal stream energy generator costs ranged from £4,800/kW (US$8,571/kW) to £8,000/kW (US$14,286/kW) with a midpoint of £6,400/kW (US$11,428/kW). They emphasized that some device concepts may have even greater capex costs but that this may be offset by future cost reductions, which would be large enough to make them economically viable. In the same study, they estimated that energy from initial wave energy farms installed in the UK would have levelized costs of energy (LCOE) between 12p/kWh (21.4 US¢/kWh) and 44p/kWh (78.8 US¢/kWh) while initial tidal stream farms were estimated to have LCOEs between 9p/kWh (16.1 US¢/kWh) and 18p/kWh (32.1 US¢/kWh). They did not take into account value engineering, economies of scale, R&D improvements, or learning curve effects.

6.7.2 Wave Energy

Previsic (2004) [TSU: Previsic et al., 2004 ?] conducted a detailed study to examine a commercial scale project costs using arrays of Pelamis Wave Energy generators. The overall plant size was assumed to be 106.5 MW (213 x 500 kW devices), at which size economies of scale were also included. Other assumptions were a full 20-year life, 95% availability and energy capture potential that took advantage of near-term R&D improvement opportunities not yet realized but which were thought to be achievable at current capex costs. Some of these assumptions may be optimistically high. The study concluded that an LCOE of 13.4 US¢/kWh is possible with a total capex of $279 million, a discount rate of 7.5%, capacity factor of 38%, and O&M costs of US$ 13.1 million annually (i.e. US$ 0.44/kWh).

This hypothetical study provides a credible benchmark to demonstrate that wave energy projects could have lower LCOEs than wind energy did in the 1980s. However, the study's optimistic assumptions about high reliability and availability of wave energy machines ignored numerous deployment problems and premature mortality experienced by early wind turbines, which were retroactively accounted for in the LCOE for wind energy technologies.

The greatest uncertainty in estimating the LCOE of ocean energy is in establishing realistic performance (energy capture) estimates and operation and maintenance (O&M) costs. Reliability and energy production levels must be estimated with some expectation that ocean energy systems will become reasonably efficient, and with reasonable repair costs, because analysts do not have the advantage of operational experience on which to base their O&M or energy production estimates. Moreover, there is a high degree of uncertainty in estimating capex costs for mature and reliable systems. Cost models assume that the machines will run for a reasonable life with a nominal service schedule (Previsic, 2004 [TSU: Previsic et al., 2004 ?]; Buckley, 2005).

An important downward cost driver for LCOE is the learning curve effect. As deployments increase and installation capacity rises, costs will move down the learning curve due to natural production efficiency gains and assimilated experience. Theoretically, every doubling of installed capacity will result in a percentage decline in costs. Early decline rates will be high but decrease over time. This learning curve effect has been documented for wind energy technologies, which experienced learning curve rates ranging from 10% to 27% per doubling of installed capacity (based on a review of nine global studies). A summary of this learning curve literature is given in Chapter 7, Table 7.8.2 [TSU: numbering changed].

Limiting this analysis to studies that span the full development of the wind industry (i.e. the 3 decades from 1980s to the present day) indicates that the learning curve effect converges to about 11% per doubling, without including an R&D factor (Wiser and Bolinger 2009). For the purposes of this analysis, it is assumed that future ocean energy industries (wave, tidal current, ocean current and ocean thermal energy conversion (OTEC)) will follow the same 11% learning curve as the wind industry. Figure 6.24 shows a wave and tidal current learning curve plot for capex only, beginning with the midpoints for the capex costs given by the Carbon Trust (2006). Given 11% learning and assuming worldwide deployments of 2-5 GW by 2020 for each technology, the learning curve would bring capex cost reductions ranging from US$ 2,600/kW to US$ 5,400/kW for both technologies, US$ 4,000/kW on average.

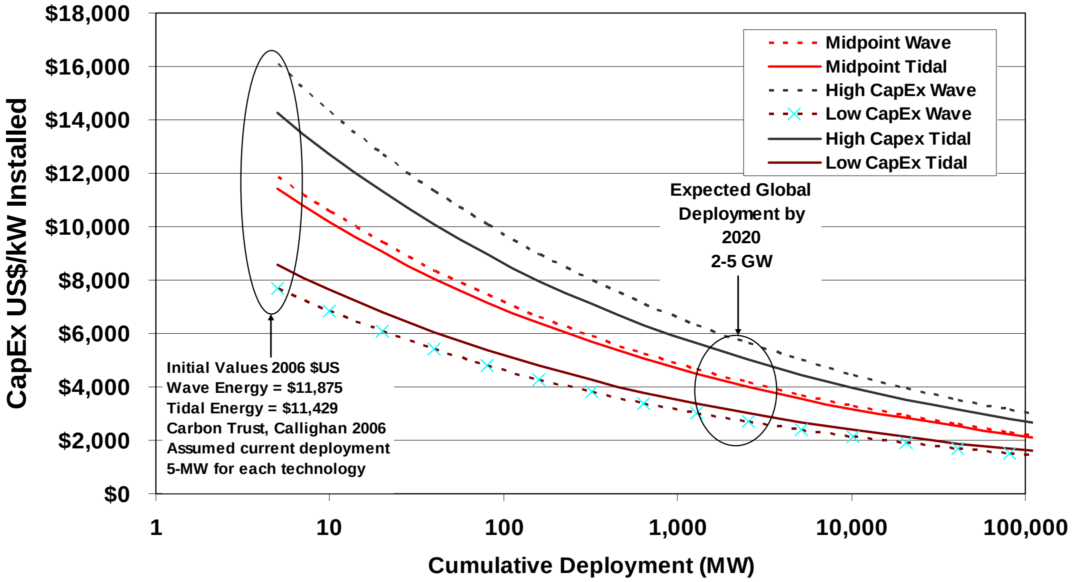


Figure 6.24: Capex learning curve reductions [TSU: Learning curves/capex reductions] for wave and tidal energy devices based on current cost and 11% cost reduction per doubling of capacity (Carbon Trust 2006).

One way to assess reliability, performance and costs together is to examine the LCOE as a function of the capacity factor. Figure 6.25 shows projections of LCOE for wave and tidal energy technologies using a calculation worksheet provided by Ryan Wiser (Wiser 2009).

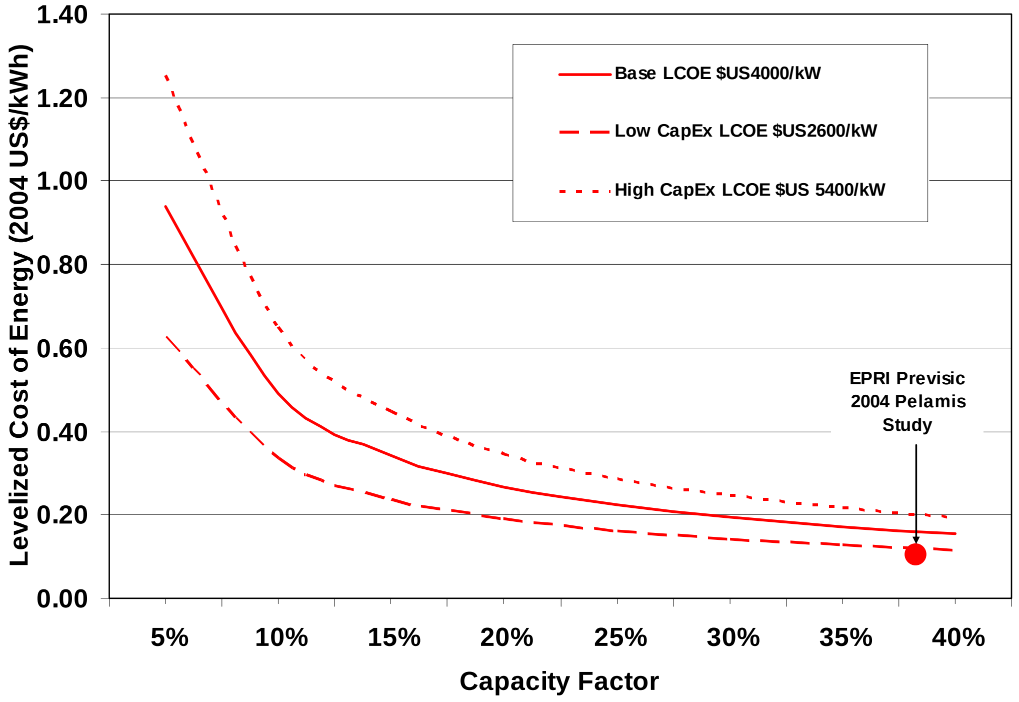


Figure 6.25: LCOE estimates for 2020 ocean energy projects and showing EPRI design point using Pelamis 500-kW Wave Power machines (EPRI, Previsic, 2004 [TSU: Previsic et al., 2004?]).

The three curves shown in Figure 6.25 correspond to the calculated high, base, and low learning curves, i.e. US$ 5,600/kW, US$ 4,000/kW, and US$ 2,600/kW, respectively. The variation of LCOE with capacity factor indicates that devices operating with high capacity factors (i.e. 30% to 40%) can potentially generate electricity at rates competitive with other technologies. However, to achieve these capacity factors devices must be optimally sited in a high quality wave or tidal current resource and be very reliable (to minimize O&M costs and energy losses due to downtime over the design life).

In addition to the learning curve effects, cost reductions through manufacturing at scale, technology innovations can also contribute to rapid LCOE reductions, as designers implement new technologies, transfer innovations from other industries and take advantage of design opportunities realized through operation and experience.

6.7.3 Tide Rise and Fall

[TSU: sources and concrete estimates missing.]

The cost of tidal rise and fall projects may appear to be a barrier to such developments. These projects usually require a very high capital investment at the outset, with relatively long construction periods. Consequently, costs associated with tidal rise and fall technologies may appear high when compared to other sources of energy. The costs of civil construction in the marine environment are very high and construction sites need to be prepared and protected against the harsh sea conditions.

Innovative techniques including construction of large civil components onshore and flotation to the site will allow substantial reduction in risks and costs. Tidal rise and fall projects tend, therefore, to be large-scale: the scale of projects reduces unit costs of generation.

The annual output of a given tidal barrage or impoundment plant is linked to the surface area (volume) of the reservoir. In a circular tidal lagoon, the surface area increases with the square of the radius, while the cost of the enclosing dyke walls is proportional to the radius. A small increase in the radius will therefore cause a nominal increase in construction costs but yield a noticeable increase in generation output.

As predictable, fully renewable projects, tidal rise and fall may be eligible for Clean Development Mechanism (CDM) credits, as was the case for the Sihwa project in the Republic of Korea or, as in the UK, for the award of two Renewable Obligation Certificates (ROCs) for tidal energy, worth £105 (US$ 191) per MWh each.

6.7.4 Tidal and Ocean Currents

It is difficult to determine the final likely costs of tidal and ocean current devices, since devices are at such an immature stage of development. A number of studies have been undertaken in recent years but these quickly become out-of-date as economic conditions change and device developments advance (e.g. BBV, 2001). Recent studies show that the unit cost [TSU: LCOE] of tidal turbines is likely to become competitive with costs of other forms of renewable energy, such as wind power (Fraenkel, 2006, Bedard et al., 2006, UKERC, 2008).

The 2006 Carbon Trust report notes that detailed design optimisation of generic device concepts could not be considered in full but that optimisation for UK resource conditions were possible (Callaghan, 2006). These optimisations are not described in detail but were estimated to contribute 5-10% learning rate cost reductions. This was attractive in order to understand whether tidal stream energy could become cost-competitive in the UK, given the country's estimated share of the worldwide resource (10-15%). Such optimisations are likely to be possible for device developments and deployments in other countries.

The Carbon Trust publication is perhaps the most authoritative recent study on the cost of wave and tidal energy-generated electricity. The study showed that the uptake of tidal stream energy and unit cost of electricity generation were intimately linked through the market price of electricity for other generation sources and learning rate (or experience curve). The study showed that initial unit costs of tidal stream-generated electricity could be high, £ 0.08/kWh (14.3 US¢/kWh) but the final costs could decline to £ 0.025/kWh (44.6 US¢/kWh [TSU: 0446 US$/kWh]) by the time installed capacity had reached 2,800 MW. Government support through either feed-in tariffs or renewables obligation certificates (ROCs) will accelerate installations and cause concomitant reduction of unit costs.

More recently a study undertaken for the California Renewable Energy Transmission Initiative showed that tidal current generation (deployed in California) would cost US$100-300/MWh (CEC, 2009).

The cost and economics for open-ocean current technologies should track closely the evolution of tidal stream energy technologies. Inherent differences between these technologies may introduce some cost variance but cost trends will be similar. No definitive cost studies are available in the public domain for ocean current technologies.

6.7.5 Ocean thermal energy conversion

Because there is no real experience yet with commercial ocean thermal energy conversion (OTEC) operations, it is hard to foresee cost trends. Literature does provide a variety of cost projections made at various times, however. These include $5,000-$11,000/kW (Francis, 1985); $12,200/kW for the 1984 plans for a 40 MW plant for Kahe Point, Oahu, or $7,200/kW for an on-shore open-cycle plant (SERI 1989), $4,200/kW, $6000/kW, or $12,300 for a 100-MW closed-cycle power plant 10 km, 100 km, and 400 km, respectively from shore, corresponding to $0.07/kWh, $0.10/kWh, and $0.22/kWh (Vega, 2002); $9,400/kW or $0.18/kWh or a 10 MW closed-cycle pilot plant, dropping to $0.11/kWh if also producing potable water (Lennard, 2004); and $8,000-$10-000/kW for an early commercial 100-MW plant, corresponding to $0.16-$0.20/kWh, dropping to $0.08-$0.16/kWh once enough plants have been built (Cohen, 2009). These estimates are in different-year dollars and cover a range of different technologies and locations. Many are also highly speculative.

The Lockheed-Martin pilot plant estimates ($32,500/kW for 10 MW pilot plant to $10,000/kW for a commercial 100-MW plant) are probably the best current cost information available for multi-megawatt [AUTHORS: Reference missing here] (Cooper, 2009; Cohen 2009). Advances in new materials and construction techniques in other fields in recent years, however, improve OTEC economics and technical feasibility. Offshore construction experience for wind turbines, undersea electrical cables, and oil drilling platforms, in particular, should prove helpful to future OTEC installations. Potentially important work specific or directly applicable to OTEC includes a congressionally mandated U.S. Navy contract expected to be awarded soon for development of high-efficiency, low-cost heat exchangers and industry and university work on lower-cost turbines. And, as with any new technology, costs can be expected to decrease dramatically as more plants are built.

6.7.6 Salinity Gradient

Osmotic power is one of the most promising renewable ocean energy sources. To utilise this form of green energy, the membrane which is the heart of the process, has to be optimized. Osmotic power has excellent environmental performance and yields CO_2-free power production. It will qualify for green certificates and other supportive policy measures for renewable energy.

The estimated costs of producing osmotic power, based on a number of detailed investment analyses, are expected to be in the range of Euro 50-100 per MWh. This is a similar range to other renewable technologies such as wind power, wave and tidal power, and power generated from biomass.

These calculations are based on current hydro power knowledge, general desalination (reversed osmosis) engineering information, and on a specific membrane target as a prerequisite. The capital cost of installed capacity is expected to be high compared to other renewable energy sources. To ensure competitiveness, given the requirement of large volumes of membranes, membrane cost and operational life will be important. However, each MW installed is very productive, with continuous operating time. This should generate approximately twice the energy supplied (GWh) per installed MW per year, compared to wind turbines, which are designed to operate an average 3,500 hours per year at various capacities.

6.8 Potential Deployment

[TSU: references missing, website links as footnotes to demonstration projects/prototypes mentioned in this section (highlighted in yellow)?]

6.8.1 Wave Energy

During the last 15 years, development of technology has being carried out mostly by enterprises (SMEs and also large industrial companies). Offshore oil and gas expertise and experience is valuable for bringing floating wave energy converter development to a commercial stage. Investors are already active in this new energy business. Unit costs of produced electrical energy claimed by technology development teams are frequently unreliable. At the present stage of technological development and for the systems that are close to commercialization, it is widely acknowledged that costs are still three times larger than those of energy generated by onshore wind (the gap is smaller when compared with offshore wind). Therefore technology developers tend to deploy their full-size prototypes in the coastal waters of the countries that provide significant incentives, e.g. in the form of high feed-in tariffs and/or access to electrical connecting cables to the onshore grid.

The Oscillating-Water-Column (OWC) type wave energy device is the most mature technology. For fixed plants, whether located in the shoreline, bottom-mounted in the nearshore or incorporated in breakwaters, OWCs can be considered as a pre-commercial technology, since various grid-connected prototypes have been in operation for many years. The cost of electricity produced by these systems is not competitive yet with electrical energy produced by other renewable energy technologies, like wind, geothermal or conventional hydro. For floating OWCs development of equipment is still underway.

Of the many floating device designs that have been developed and deployed, only Pelamis has become a pre-commercial technology. The first 3-unit Pelamis wave farm was deployed off Portugal in July – November 2008.

Full-size floating prototypes are planned to be deployed in specific test sites that are being created in various countries, including Norway, UK, Ireland, France, Spain and Portugal. Financial support by the European Commission has been instrumental to technology development and presently enables the construction and testing in the sea of a number of full-scale prototypes. This is the reason why Europe is leading the development of ocean energy technologies. In the USA the first federal support grants were awarded in 2008, whilst in Canada federal and regional government programmes (in British Columbia, Nova Scotia and New Brunswick) have been developed. In Brazil principal developments are being encouraged by a mix of private and government financial support.

6.8.2 Tide Rise and Fall

The world's largest tidal power plant (254 MW) is currently under construction at Sihwa in Republic of Korea. The plant has been installed in an existing dam and will incorporate 10 bulb turbines, each rated at 26 MW, with a runner diameter of 7.5 m. Korea has also announced other larger tidal plants, for example, a 520 MW barrage planned for Garolim Bay (Shanahan, 2009).

In the United Kingdom the 14 m tidal range in the Severn Estuary has long been considered, as one of the greatest tidal sources to be harnessed. Ten proposals to generate electricity were submitted from a public call for proposals in May 2008. Proposals were made at a variety of scales (ranging from 624 MW to 14.8 GW) and included barrages, offshore lagoons, continuous line of underwater tidal current turbines and a tidal reef. The British Government is currently considering these proposals.

6.8.3 Tidal and Ocean Currents

A series of devices to produce electricity from tidal currents are presently in different stages of development, some of them already deployed (OES-IA, 2007). In addition, new tidal stream devices also entered the field in 2008. A number of large tidal stream developments are planned over the next five years, based on 1 to 1.5 MW turbines from different manufacturers (Bahaj, 2009).

There are many different designs of tidal and ocean current turbine devices and there is presently no single convergent designs. The European Marine Energy Centre website lists 53 different designs of tidal and ocean current devices (see website in references [TSU: websites as footnotes]). Design options include horizontal versus vertical axis rotation, turbine types (2- and 3-bladed rotors, ring turbines), mounting (seabed, mid-water and surface-piercing). However, it is true that submarine devices, similar to wind turbine generators, are beginning to dominate. These devices have a horizontal axis turbine with an up-current 2- or 3-bladed rotor fixed to a vertical tower, which is either gravity-based or drilled into the seabed.

The most developed device is the Marine Current Turbines' "Seagen", which is similar to this concept, except that it has two generators on a horizontal hydrofoil. This device has been generating electricity in Northern Ireland since July 2008. The developers describe it as a 'pre-commercial demonstrator'. There is thus no commercial tidal or ocean current device presently available.

Tidal currents are created by the tidal range and, in most cases, constrictions caused by submarine topography, such as narrow passes between islands and the mainland. The deployment of tidal current devices is thus likely to be areally restricted. The best locations for such deployments include Canada (Bay of Fundy, Vancouver Island), Scotland (Pentland Firth), Wales (Anglesey), Korea (Uldulmok) and New Zealand (Cook Strait). Wider deployments of tidal current devices will depend on careful examination of individual sites. Current conditions will determine not only the selection of turbine types but also the micro-siting of individual turbines in an array.

Ocean currents are much more widespread than tidal currents but generally operate at slower speeds, which may be too slow for most devices. Harnessing slower ocean currents may require some specific device designs. These designs are likely to be based on similar principles to tidal current devices. Perhaps the best example is the Gulf Stream off Florida, which has been shown to have the potential for up to 10 GW of installed ocean current capacity.

6.8.4 Ocean thermal energy conversion

Ocean thermal energy conversion (OTEC) offers a large potential for long-term reduction of carbon emission through many of its aspects. Power production directly translates to substantial avoided CO_2 emissions. Cooling using deep ocean water can also displace the use of fossil-based electricity. Production of drinking water using renewable energy, which is likely to be a highly sought-after commodity in coming decades, will be central to meeting future world demands responsibly. Mariculture and aquaculture using nutrient-rich cold ocean water can enhance local economies without fossil fuel use.

For the near-to-mid-term, the potential to use OTEC power is likely more limited by appropriate markets than by any constraints on the resource. Small onshore or nearshore multi-use plants could contribute a modest amount of total energy but could prove to be highly significant to local economies for many small island nations. Ocean energy could be the catalyst for many of these nations to become independent of imported resources for power.

Larger floating-platform OTEC plants sending electricity to shore by submarine cable are likely to be limited to large populations in locations such as Oahu, Hawaii; Puerto Rico; U.S. Gulf Coast cities (Tampa, Key West, New Orleans and Brownsville and perhaps the southeast Florida coast). Cuba; Taiwan; the Philippines; and India all have large sea water temperature differentials close to shore with large coastal populations nearby. In the long term, ‘grazing’ plant ships could conceivably begin to approach resource limits but more likely would be limited by ability of economies to utilize ammonia or other “high-energy products” directly or indirectly for transportation fuel or other purposes. Adaptation of motor vehicles to use ammonia as fuel for internal-combustion engines or ammonia-derived hydrogen for fuel cells could be a key research and development area in this respect.

6.8.5 Salinity Gradient

The Statkraft prototype plant, which became operational in October 2009, is an important milestone following several years of osmotic power research & development (R&D). In addition to further development, it is intended to be a meeting place for parties from governments and industries with ambitions or commitment to this new and promising technology.

With increased focus on the environmental challenges and the need for more clean energy, the prototype plant is a significant contribution to the generation of renewable energy and increases the momentum in development of new clean technologies.

In the longer term, technology development at the operational prototype plant will be used as a basis to develop a pilot plant with an installed capacity between 1 - 2 MW within 2 - 5 years, bringing the technology one step nearer to commercialisation and development of full-scale plants (Scråmestø, Skilhagen and Nielsen, 2009).

Like most new technologies, this technology will need governmental assistance with support schemes in the early development phase to make it economically attractive. Given continued technology development and declining prices for components, osmotic power is a realistic technology with huge potential for renewable energy generation.

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